RAINFED AGRICULTURE IN A SEMI-ARID TROPICAL CLIMATE
Aspects of land- and watermanagement for red soils in India

India's great potential for more food production is in its drylands.
Ch. Krishnamoorthy, S.L. Chowdhury and E.D. Spratt (1974)

Promotoren: ir. L. Horst, hoogleraar in de irrigatie
dr.ir. W.H. van der Molen, hoogleraar in de agrohydrologie

F. P. Huibers

RAINFED AGRICULTURE IN A SEMI-ARID TROPICAL CLIMATE

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PROEFSCHRIFT

ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
op gezag van de rector magnificus,
dr. C.C. Oosterlee,
in het openbaar te verdedigen
op vrijdag 22 maart 1985
des namiddags te vier uur in de aula
van de Landbouwhogeschool te Wageningen

Voor Ingrid,
Loek en Stefan

NNO8201,1028

PROPOSITIONS

1. The conclusion that "55 - 70% of the seasonal rainfall on Alfisols either runs off or drains to deeper layers" is incorrect.
   S.A. El-Swaify, T.S. Walker and S.M. Virmani (1984). Dryland management alternatives and research needs for Alfisols in the semi-arid tropics: 14.

2. By including seeders with precision metering as attachments to the bullockdrawn wheeled tool carrier, as suggested by ICRISAT, an unnecessary, troublesome and expensive element is added to an otherwise practical unit.

3. Systems indicated as "reduced tillage" and "no-tillage", as developed in North-American agriculture, suggest being simple and energy saving compared to "conventional tillage". In reality they belong to the most highly developed and capital intensive agricultural systems and are of very limited use to developing countries.

4. In the sphere of applied research, the collection, adaptation and combination of available know-how may often lead to a faster, cheaper, better and more widely applicable result, compared to the initiation of new experimentation. In this respect international agricultural research institutes have an important role to play.

5. Considering the large number of widely differing interpretations of the terms "farming system" and "farming systems research" it is clear that the use of such terms is more often based on opportunism than on a scientific approach.

6. In situations where the crop cover does not extend over the entire soil surface it is necessary to model separately the processes of transpiration and evaporation.
   Jury, W.A. (1979). Water transport through soil, plant and atmosphere. In A.E. Hall, G.H. Cannell and H.W. Lawton (eds.): Agriculture in semi-arid environments.

7. In the semi-arid tropics, probably more than in other climatic regions, irrigation water does not have the scarcity value it should have on the basis of socio-economic considerations. Distortions may be caused by technical reasons, as well as by local elitism and political interests.

8. In low-input agriculture small-holders are, in general, the most efficient users of resources. Development plans should take more note of this.

9. In general, energy can be supplied more efficiently and at lower costs when it is decentrally generated. It is in the interest of many developing countries if the involved technology, required by such a strategy, is further developed and adapted.

10. Inkomende telefoongesprekken krijgen vaak ten onrechte een voorkeursbehandeling.

F.P. Huibers. Rainfed agriculture in a semi-arid tropical climate. Aspects of land- and watermanagement for red soils in India. Wageningen, 22 March 1985.

PREFACE

On the basis of an agreement between the Government of the Netherlands (Directorate General for International Co-operation, DGIS) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), I worked as an associate expert within the Farming Systems Research Program of ICRISAT in Hyderabad, India, for a period of four years. This has given me the opportunity to get acquainted with the semi-arid region of India, its people, the institute and the research on land- and watermanagement. After this period, both DGIS and the Agricultural University of Wageningen enabled me to proceed with the subject of land- and watermanagement and to compile and complete my research with the writing of this thesis. For all this support I am very thankful.

The idea to write this thesis was conceived during the early part of my research work at ICRISAT. It started as an initiative of Dr. B.A. Krantz, at that time the head of the Farming Systems Research Program, and was supported by Dr. J. Kampen, then leader of the Land- and Watermanagement Subprogram. At that moment, the decision to proceed was positively influenced by the conception that it could result in the incorporation of aspects of rainfed agriculture into the study "tropische cultuurtechniek" at the Agricultural University Wageningen, which was historically almost exclusively oriented towards irrigated agriculture. I am glad to note that indeed the interest for and activities on this subject have increased tremendously in recent years. To a large extent this should be attributed to the activities of a group of students who suggested the introduction of a course element on rainfed agriculture.

I appreciate the role of my promotors. At an early stage, contact was made with prof. ir. L. Horst, who showed great interest in my work and since then has continued to support me, also by enabling me to work at his department. His suggestion to request prof. dr. ir. W.H. van der Molen to take part as promotor proved to be very valuable. Van der Molen's interest in the

subject and his long-standing experience as promotor has helped me much to improve on earlier drafts of this thesis.

During the period of experimentation, I have depended on many persons (too many to name individually) who I would like to thank for their collaboration. Among the scientists of the Land- and Watermanagement Subprogram I am especially obliged to Mr. K.L. Srivastava, who for all years since 1981 functioned as a pleasant and efficient contact person. I would like to thank all field assistants I worked with, especially Mr. P. Kistaiah, the late Mr. Y. Buchi Reddy and Mr. L. Nageshwara Rao. My appreciation also goes to Dr. M.B. Russell, with whom I had extended discussions on the subject. I am grateful to Dr. S.M. Miranda, head of the Land- and Watermanagement Subprogram between 1980 and 1982, for his support and hospitality during my later visit to ICRISAT.

I further acknowledge the technical support and advices of Mr. S.K. Sharma and his crew, the co-operation of Mr. S.R. Patel, who worked with me for some time and the experimental work done by ir. S.J. Weststeyn during the 1982 rainy season on which results I also draw.

While writing this thesis I have made fruitful use of comments and help given by ir. N.V. Vink, prof. dr. ir. H. Luning, ir. W.B. Hoogmoed and others. I am thankful to them.

Much technical work is to be done before the final printing of a thesis. Mrs. F. Jacobs-Wien did a seemingly endless job in typing most of the drafts, Mrs. J. Millican took care of the English correction, while Mr. F. van Ernst drew the figures. My thanks to all of them. For the final typing I am obliged to Mrs. M. van Hunen who worked hard to finish in time.

I feel grateful to my mother and my late father who valued education highly.
I have appreciated the interest shown by many.
Particularly I am indebted to Ingrid for her continuing encouragement and help.

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CHAPTER 1 INTRODUCTION

For millions of people in semi-arid tropical regions rainfed agriculture means a harsh fight for survival. They rely on agricultural systems that are generally traditionally organised. For crop-growth, the local precipitation is the only source of water, and its availability further depends on the moisture acceptancy and crop-available storage capacity of the soil profile. Rainfed agriculture differs from irrigated agriculture where, through a more or less man-controlled transport and distribution of water, its availability for crop-growth is secured to a certain level. Likewise it differs from dry farming, (common for some arid regions), where rainfed crop production is no longer possible (UNESCO, 1977), but where techniques are used that concentrate water in time or in place *(Chapter 4)*, to enable local crop production.

Contrary to other systems, rainfed agriculture completely depends on the local precipitation as water source and, as in dry farming, the profile to store it. But the high variability of rainfall, typical of a semi-arid tropical climate results in the occurrence of low rainfall years and dry spells during the rainy season *(Section 5.2.)*, affecting crop-growth adversely.

The semi-arid tropical zones cover part or all of 48 less-developed countries. Extended areas can be found in Africa, north and south of the Sahara, and in India (Ryan and Binswanger, 1980). Among the developed countries Australia obviously has an extended semi-arid tropical region. It is useful to differentiate between the semi-arid tropical regions of the world on the basis of their population density *(table 1.1.)*, depicting India as by far the most densely populated part.

But, apart from the difference in population pressure, there are differences in farming systems, the latter defined as the entity of available

Table 1.1. Area and population of some semi-arid tropical regions

Region	Geographical Area	Rural Population	Population Density
	1,000 km^2	million	inhabitants/km^2
Asia	2,200	300	136
(India+)	1,700	260	153)
Africa South of Sahara	11,500	157	14
Australia	1,920	1	< 1

+) Major irrigation schemes excluded

Adapted from Ryan and Associates (1975).

technology, the decisions the farmers make and the circumstances that influence these.

In the African semi-arid tropical zones, for example, there was, until recently, an abundance of land. In many locations, availability of land is no major constraint even nowadays. Much of the area is used for grazing and animal husbandry forms an important resource. Arable cropping mostly takes place at a low level of technology based on the traditional system of shifting cultivation that used to be an adequate technique to maintain reasonable fertility and to provide soil protection.

In India livestock forms a different and less important component of the farming system. Most farmers do own some animals for the sake of milk-production, draft and manure. The relatively high population has always forced the farmers to follow a system of farming in which all suitable land was cropped yearly. The steep increase of the population in the course of this century, caused new areas to be brought under cultivation, bringing about an inbalance between forests and cultivated land and an increase in the cereal component at the expense of legumes, resulting in a depletion of the soil nutrients and a poorer feed for draft-animals (Krishnamoorthy, 1974).

In Australia (Bowden, 1979), an agricultural minority produces for a non-agricultural majority. Such a situation allows for a farming system based on mechanisation and scientific usage and exploitation of the environment. An important characteristic of such a system is the presence of infra-structure and buffer capacity of the non-agricultural sector that is able to support the agricultural sector during periods of stress.

Much of the semi-arid tropical zone of the world is inhabited and taken into agricultural use. Historically, this can be understood by the relatively favourable living conditions of these areas, compared to the more humid areas, infested by vector-borne diseases and the more arid areas that by their water shortage lacked the conditions to produce food.

Per hectare production levels in the semi-arid tropical areas are generally low, which is not only related to the frequently sub-optimal availability of water. A range of economic and social factors, like an increased food demand and the introduction of cash crops (Mascarenhas, 1968, cited by Jackson, 1977) have forced the farmers in many regions to leave their traditional systems which were much more well-oriented towards maintaining fertility and also produced surplus as relief for bad rainfall years (Krishnamoorthy). At present, many such areas are characterized by frequent food shortage and poverty, forcing producers towards an attitude oriented at risk avoiding and decreasing their means to invest.

Traditional agriculture, based on a long history of experience and decision making is, as Schultz (1964) explains, in a state of equilibrium, in which the (traditional) factors of production available are used as efficiently as possible under the prevailing circumstances. This idealized situation, however, hardly exists today. Although much of the agriculture still depends on traditional knowledge, social values and inputs, other circumstances are disrupting this state of equilibrium more and more. Bowden (1979) even states: "None of the present dryland (rainfed) farming systems are in balance with the environment as they deplete more and more of the resource base". This remark deserves our full attention. Leaving aside the question whether or not *all* present farming systems should be blamed, it *is* true that, at an alarming rate, land has been and still is being converted into arable fields that do not have the proper characteristics for this use, either by its topography or its physical or chemical properties; and that traditional farming systems, proven to be able to maintain the soil as natural resource, have been replaced by systems that deplete it under pressure of the need for more production; and that techniques have been introduced into traditional systems without proper care or knowledge of their long-term consequences on the environment.

People do need food and additional production to take care of their other basic needs like clothing, housing, medicare and education. It is their right to work the land to try to get this. It is painfull to see that, while making use of this right, the natural resources are being over-stressed, resulting is declining productivity.

Much of the cultivated land in the semi-arid tropics is vulnerable to degradation. This is especially true for the sandy and sandy loam soils, generally called the red soils, the most widespread soil type in the semi-arid tropics (Sanchez, 1976), and on which soil-type I want to concentrate. Red soils have a low aggregate stability, resulting in slaking of the aggregates upon wetting, an easy formation of a crust upon drying, compaction of the top layer and a flattening of the surface when exposed to rainfall. These processes reduce the permeability of the topsoil and reduce the capacity of surface storage. The consequent surface runoff causes high levels of erosion, bringing down the useful profile depth and fertility. Over the years this results in poorer plant growth, meaning lower yields and even less protection against the raindrop impact. In this spiral of events the soil and water are important factors. And water is clearly the least predictable, sometimes being short, affecting crop-growth, sometimes in excess, acting as a threat to the valuable soil and soil-fertility.

With annual rainfall amounts from roughly 500 mm to more than 1,000 mm sufficient water seems to be available for reasonable to good yields of most crops (the actual water requirements of most crops are much lower (Hall *et.al.*, 1979)). Even the high level of potential evaporation in this climate could hardly counteract this, as water losses through direct evaporation are relatively low during the rainy season due to cloudiness, reduced temperatures, early topsoil drying and protection by the vegetative cover. Other characteristics of the rainfall, however, its variability over the years, its high intensity and its uneven distribution over the season, exert a negative influence on the water availability, and are most pronounced for red soils. Rainstorms with intensities exceeding the infiltrability cause the build-up of free water on top of the soil surface. Apart from a generally small amount of water that is caught in surface depressions, the rest of the water will run off and be lost for the crop. As a contrast to the generally high infiltrability of sandy soils, the actual infiltrability of the red soils can be low and frequently below rainfall intensities, because of the slaking of the surface layer. Prolonged dry spells affect crop growth if insufficient moisture is stored in the rooted profile for the crop to draw from. Again, the red soils should be considered as problem soils as their depth is frequently low as is their moisture retention capacity.

Against these negative characteristics, positive ones can also be placed. The low water retention capacity causes a deeper infiltration of small amounts of rain, which, in specific circumstances, could allow for a faster availability of water in the rooted part of the profile. It also reduces the total amount of water that is lost by direct evaporation. Red soils have the further advantage that they permit an early access to the field after rain, being easy to work when moist.

As indicated earlier, the circumstances that cause the generally low level and instability of production are manifold and complex. Some of them are related to the environmental conditions, others are man-made. And although it clearly is not just the water availability that determines the farmer's destiny, it can be stated that, aiming at improving production in the present situation, an important approach would be to try to both secure a better availability of water throughout the growing season as well as to make the most efficient use of it. For the latter, crop adaptation, -rotation and -management are important in reaching these goals, as they have always been used by the farmers of the semi-arid tropics. Present day knowledge of breeding techniques and of fertilization and plant protection only add to their potentials.

In the field of land- and watermanagement a contribution could be made in providing the necessary techniques to improve the water availability through reducing water losses, through increasing the system's water storage capacity and through transfer of water in place or time. It could also improve the soil-plant environment by taking care of good drainage and allowing for proper and timely tillage. Besides this, activities on land- and watermanagement include design and management measures to protect the soil against degradation by erosion and the provision of an appropriate infrastructure, supportive to agricultural activities.

Among the research institutes that concentrate on the improvement of rainfed agriculture in the semi-arid tropics is the International Crops Research Institute for the Semi Arid Tropics with headquarters near Hyderabad, India, from here onwards referred to as "ICRISAT". Part of its efforts are concentrated around the crop improvement and crop-related programmes, having a special mandate for the improvement of Sorghum, Pearl Millet, Groundnut, Chickpea and Pigeonpea, (ICRISAT, 1977), all crops typically grown in the semi-arid tropics and, internationally, mostly disregarded before. Besides this, ICRISAT has a strong Farming Systems Program as well as a Socio-economic and a Training Program.

Evidently, although ICRISAT has set the efforts for improving rainfed agriculture in the semi-arid tropics in a concentrated and world-wide context, national reasearch organisations have preceded it and still are major contributors in many countries, mostly focussing their attention on adaptive research. For the Indian situation the All India Co-ordinated Research Project on Dryland Agriculture (AICRPDA) should be mentioned, representing a nationwide chain of research centres of which the first started work over fifty years ago.

Within the Farming Systems Research Program of ICRISAT attention has been concentrated for many years on research into improvement of the management of the deep Vertisols. A system has been evolved that includes the use of improved varieties, fertilizer, bullock-drawn equipment and land management. The system has great potential for increasing food production, at the same time reducing erosion, for many parts of the semi-arid tropics. Although a range of constraints, most of them in the sphere of farmer's group action and credit facilities still have to be solved, the envisaged approach deserves detailed evaluation at a regional level.

The concentration of research attention towards the Vertisols, at the same time obscured management problems that are more specific for the red soil areas. One might say that research was mostly climate oriented rather than soil oriented. It was only later that it was realized that the red soils management in the climatic conditions of the semi-arid tropics would possibly need a different research approach.

In this presentation I want to give such an approach, viewed from the possibilities of influencing the availability of water under the climatic, socio-economic and topographical conditions encountered in many of the red soils areas of India. It is placed in the context of more general as well as historical techniques for water management, for which the applicability to the red soil areas is discussed.

Research data in this presentation originate mainly from my work at ICRISAT-station and some of its village research locations in India. In the Farming System Research Program and, more specifically, the Land- and Watermanagement subprogram to which I was assigned, research is done wherever possible in an integrated way. This also means that individual researchers can frequently make use of each other's findings and observations, an approach on which I also draw. Research aimed at improving rainfed agriculture is no field for individuals, but does require close cooperation and the understanding of many disciplines. This seems most true if research is oriented at aspects of land- and watermanagement, which are always parts of a more complex system, and are difficult to separate from it. This presentation, therefore, should also be seen as a synthesis of ideas, observations, measurements, options and discussions, drawn from many people; for the way in which they are used here, I certainly bear the responsibility.

CHAPTER 2 RAINFED AGRICULTURE: ITS OCCURRENCE AND DEVELOPMENT

2.1. Agriculture: Its Early Development

In its simplest form, agriculture is an activity to produce food. It is a technique in which a single or a few types of plants are nursed on a piece of land, limited in area, which is prepared for it. The beginnings of agriculture are thought to date back to about 10,000 years B.C. (Reed, 1977). The scale of hypotheses on the driving force for man to shift from hunting and gathering to agriculture were reviewed by Cohen (1977), who concluded that this change could only be accounted for by assuming that hunting and gathering populations had exhausted all possibilities for increasing their food supply within the constraints of their life-style. If so, it can be understood that, as Lawton and Wilke (1979) state, a "surprising number of early agricultural economies developed in drier regions of the world".

While primitive agriculture was solely oriented towards production for own survival, a change occurred at the time mean production started to exceed food requirements. This happened in dry areas where agriculture could make use of additional water, brought to the fields through controlled or uncontrolled means *(Section 4.1.)*. Trading the excess yield, and changing production patterns to include non-food crops, made agriculture much more of an enterprise. Optimizing production became more and more important and historic societies with a relative advantage in agricultural production, could develop important political powers. The greater freedom of diseases in semi-arid areas compared to the more humid zones, together with a better diet, were probably the cause of more powerful political entities in these regions than elsewhere, with higher population densities (Bowden, 1979).

Apart from its role as food producer and its economic importance, agriculture should be seen as a part of the ecological environment. This aspect tends to manifest itself as a longer term relation, as improvements of or damages to the environment are expressed in changes of net benefits in production mostly only after years or tens of years. Agriculture changed the natural environment through overgrazing by domesticated animals, clearing of forests, introduction of alien weedy species, soil erosion and the destruction of native fauna. Inherent in the system is a higher but uncertain production level, variable over the years, as yields depend on weather, weed competition, plagues and diseases.

Agricultural activities could even affect the pure existence of the society. Referring to a publication of Lowdermilk (1953), Hudson (1971) remarks that "studies on the effect of erosion on early civilizations have shown that a major cause of the downfall of many flourishing empires was soil degradation".

2.2. Agricultural Development in Modern Times

Attention given by governments in modern times to agricultural development differs. It is in turn intensively supported or largely neglected. Investments in agricultural infrastructure generally pay-off slowly, particularly if development projects include long term protection of the production factors soil and water. A faster recovery of the capital only proves possible through a drastic change in the traditional production pattern, which very often disrupts the social, economic and/or ecological equilibrium of the existing form of agriculture. The consequences of this are not always foreseen or understood.

A slower, un-forced development can also have strong negative effects. The increase of population density in many agricultural areas has been, and still is the reason for expanding agriculture beyond the capacity of the environment at the level of available technology. Land not really suitable for crop production is taken into use as the produce of the more suitable land cannot fulfill the food requirements. For this reason, many of the shallow red soils in India have been converted into arable land and grassland areas are overgrazed. A similar trend can be seen in the influence of an expansion of the area under cash crops. Competition for land results in taking less-productive areas into use. Further increase of population may lead to an increase of the cereal component at the expense of legumes, leading to a depletion of the soil nutrients, and poorer feed for the draft-animals (Krishnamoorthy *et. al.*, 1974). The most general consequence of this is a further deterioration of the land, mainly through leaching and erosion. Even optimal stands of row crops can never give the same protection against erosive rains as a good natural vegetation.

In India, this trend towards decreasing mean production levels per hectare could just be balanced by the farmer's accepted new techniques during the last fifty years. Relating to data given by Randhawa and Venkateswarlu (1980), present farmer's yield levels compare with those obtained at research centres in the thirties. Meanwhile, production potential has jumped to values that are a multiple of these, which are, however, only reached under optimal conditions.

2.3. Soil and Water

The soil profile, as the medium for root-growth has an important function in the acceptance, storage and release of water and plant-nutrients. Although these characteristics are strongly related to the physical factors of soil (texture and structure), their actual values also depend on external factors, like crop (depth of rooting), climate and management.

Soil-profiles that can be deeply rooted and are characterized by a high percentage of crop available water, have a buffer-capacity, making them less dependent on the rainfall distribution. An example is formed by the deep and clayey Vertisols of many semi-arid areas. More sandy soils and shallow soils, on the contrary, have a much lower retention capacity and the distribution of rain should therefore be regular enough to avoid crop water stress. An example of these are the shallow red soils, also common in semi-arid tropical regions.

Infiltrability of the profile is another important differentiation between soil types in respect to their water balance. While coarse-textured soils tend to have higher infiltration rates, the slaking of the unstable surface aggregates could create surface sealing that reduces the infiltration of water considerably. This is typical of the red soils. Rainstorms with an intensity exceeding this reduced infiltration rate will partly run off, even when the profile is not saturated.

Most agriculture in the world is rainfed, which means that the crop fully depends on the local precipitation for its water supply. In areas where the rainfall exceeds the potential evaporation only during a certain period of the year, rainfed crop production is roughly limited to that period for soils, that have a moderate to low moisture retention capacity, like the red soils. The semi-arid tropics are an example of this where on average, only 2 to 4½ months of the year can be considered as humid *(Section 3.1.)*. Under certain conditions, mainly determined by the presence of soils with a high storage capacity of water available for plants, the cropping period could be chosen directly after the humid season. The high variability of rainfall, common in these areas and the incidently high intensities of rainstorms, make water an important and unpredictable parameter, sometimes being short, sometimes in excess and often aggresive in its erosive power.

2.4. Irrigated Agriculture

If (temporary) shortage of moisture from precipitation makes crop production impossible, risky or unproductive, the availability of water, transferred from other sources to the location of shortage, could improve the agricultural potentials considerably. This happens in natural conditions (flood plains) or can be done by artificial means (irrigation).

In arid areas no permanent agriculture is possible without import of water. In semi-arid areas it is, but irrigation would make it possible to increase and stabilise production, and extend the growing season to include more crops per year or enable introduction of more water requiring crops.

In the semi-arid tropics, easily accesible water resources are insufficient for widespread irrigation. Locally, near rivers or in areas with an ample groundwater supply, technical developments could be conceived that make this water available for crop production. Implementation of such irrigation lay-outs would generally require a high level of capital investment per unit volume of water, that would only be economically feasible if production was not hampered by further restrictions like poor quality soils or irregular topography. In much of the semi-arid tropics, irrigation would become too expensive to be paid for by the projected increase of production.

2.5. Irrigated versus Rainfed Agriculture

A number of modern inputs can, technically seen, be easily introduced into any environment like selected seeds, machinery and chemicals. The pay-off of such inputs could be high but is often brought down by a limiting water supply. Irrigation, therefore, is considered as having a snowball effect on agricultural production in areas with marginal or insufficient water-supply, and attempts to increase agricultural production often concentrate on the introduction of irrigation systems.

The high development- and operation costs of irrigation systems frequently force the users to produce crops with a maximum economic profitability, that can be traded in order to pay for water-rates and other costs, even if, as stated by Carruthers and Clark (1981), levied rates are mostly below real costs. In irrigated agriculture a shift can be observed towards a few commercial crops, reducing the diversity of the agro-ecosystem (Murton, 1980).

Depending on the availability of the resources land, water and capital, irrigation lay-outs are bound to be restricted to an area limited in size and therefore project-oriented. The combination of concentrated development, high capital input, drastic change in production pattern and great economic interest of many parties involved, easily lead to personal and political involvement, and risk making the execution of an irrigation project an object of prestige. This often causes a lack of interest in the development of surrounding areas. As a consequence of this, the relatively small irrigated areas receive the lion's share of resources like fertilizers and extension services, initially allocated for the whole region, and seasonally draw labourers and small farmers through higher wages from rainfed areas, leaving their own crops uncared for (Jodha, 1978).

A similar effect can be observed on a much smaller scale where farmers have their land partly irrigated, partly rainfed. Rao (1978) observed that the farmers "neglect the rainfed area to reap the benefits of the irrigated land". According to Sanghi and Rao (1982), in the Hyderabad region, India, the 10 per cent area under irrigated crops usually receives 90 per cent of the farmers resources and attention.

As a contrast to irrigation, rainfed agriculture in droughty areas has always received much less attention. In water limited agriculture, the use of improved inputs does not seem to pay off well and is risky. Farmers in developing countries, often producing at subsistence level are mostly unable to obtain the necessary capital, and cannot afford to take risks. Therefore they tend to keep on working according to their traditional systems, using the same implements, seeds and fertilizer.

Moreover, development of rainfed areas in semi-arid tropical regions would include expenditures that are oriented towards resource conservation rather than directly productive aims. Improvement of the productivity of rainfed areas does not automatically include the possibility of introducing cash-crops; much of the extra produce of food crops might be directly consumed to make good existing food deficits, while the marketable part will not always meet a purchasing power.

Yet, leaving aside the complications of economic interests, a well-balanced introduction of improved technologies has proved able to increase production of rainfed crops tremendously on the experimental stations (Kanwar, 1980), and likewise at farmer's level distinct yield advantages have also been observed (ICRISAT, 1982). Although yield increases in rainfed agriculture on hectare basis will never be as impressive as those attained through irrigation, the potential of irrigation is restricted by the availability of recoverable water. The importance of rainfed agriculture is different, because of its main orientation towards the production of subsistence crops and because of its huge area that could benefit from improved technologies.

2.6. Rainfed Agriculture and Erosion

Soil erosion is a problem strongly related to rainfed agriculture. Wind and water, the main erosive factors, have free play on land that is unprotected by natural vegetation. Crops, esp. if rainfed, provide a lower level of protection and for only part of the year. Extending agricultural land leads to the incorporation of more erosion-susceptible areas, that were left before because of poor quality or topography.

Realising the need for sufficient production land, erosion control measures have to be taken within the system of farming. In this, improving agricultural production and reducing erosion may go side by side. Better crop growth can decrease erosion through better canopy development and higher water use, giving better protection to the soil surface and reducing runoff respectively. Better erosion control along with water conservation improves the basic resources for crop production.

2.7. Land and Watermanagement in Rainfed Agriculture

In this study, attention is focussed on the land- and watermanagement of red soil areas in the semi-arid tropical climate of India. This is part of a general objective of institutions like ICRISAT and AICRPDA to develop rainfed farming systems that increase the agricultural output and stabilize it in terms of yearly variability and long term productivity.

A major constraint a farmer faces is the uncertainty of timely availability of sufficient moisture. As already indicated, the low profile storage of red soils and their poor water intake, make this moisture availability aspect more important than with some other soil types in the same climate.

The effects of a more secure moisture availability could go much further than the simple (unifactoral) water-crop growth relation. It might open up the possibility of introducing improved varieties with higher yield potential under improved conditions of fertilization and plant protection. This, on the other hand, does need a well-managed and uniform crop environment, much more so than with local varieties.

Methods to influence the water availability can be split into two approaches, either oriented towards conserving rainwater *in situ* by improving the infiltration and storage capacity of the profile, or a system in which excess water is collected and stored for later use. The first approach is limited to the level of profile storage capacity, the second has no such limitation, and a potentially long carry-over effect but requires higher investments.

2.8. The Watershed Approach

The important role water plays in rainfed agriculture, being short or in excess, makes it useful to select what we will call a watershed as a hydrological unit of attention. Strictly speaking, a watershed is the topographic division between two areas from where surface runoff contributes to different river systems or lakes. In American literature the term watershed, however, is being used to indicate the undivided area, from which runoff water collects at one point. In this definition, watershed is in a sense synonymous with catchment area or drainage basin (Institute of Hydrology, 1982). These terms, however, are generally used to indicate the total runoff contributing area of a river or lake which could be a complex system. A watershed could also be defined as an area that forms a topographical unit with a single drainage outlet, forming part of a much larger drainage basin (Smith and Woolhiser, 1971). Further refinement of the watershed definition is done incidently on the basis of size range (Rao, 1980), but as there is no universal agreement on this, it remains necessary to define the terms whenever used.

In this study attention is concentrated around "small agricultural watersheds", not exceeding about 20 ha in size, that are completely or for the most part in use for annual crop production *(See also Chapter 9)*. As a consequence of the small area involved and of the objective of runoff manipulation, the important hydrologic features of such watersheds are precipitation, infiltration, evaporation, percolation and surface runoff. It should be remarked that, in the area studied, subsoil water movement is not important as useful aquifers do not exist. Water leaving a watershed area as subsurface flow, if taking place at all, should therefore be considered as percolation loss, while subsurface inflow is not considered.

CHAPTER 3 THE SEMI-ARID TROPICS AND ITS AGRICULTURE

3.1. Definition of the Semi-Arid Tropics (SAT)

Most systems of climate classification are based on air temperature and precipitation. The criterion developed by Köppen (1936) in defining the tropics is widely used. He selected the 18°C isotherm, indicating the mean temperature of the coldest month as the lower limit. The tropics, therefore, do not experience cold periods and crops requiring heat to mature, can be grown throughout the year if water is no constraint (Virmani *et. al.*, 1980).

Availability of moisture is not only dependent on the amount of precipitation. Classification systems have different ways of indicating the moisture availability, in order to define the humidity or aridity of an area in the course of a year. Thornthwaite (1948) proposed a waterbalance concept, based on potential evapotranspiration and precipitation, defining a moisture index (I_m) as:

$$I_m = I_h - 0.6\ I_a = \frac{100\ S - 60\ D}{PE} \qquad (3.1.)$$

with: S = Mean annual moisture surplus (mm/a).
D = Mean annual moisture deficit (mm/a).
PE = Potential evaporation (mm/a).
I_h = Humidity index (-).
I_a = Aridity index (-).

A semi-arid area has a moisture index range of -40 to -20. Moisture surplus and deficit are calculated on the basis of a number of assumptions. The moisture index, I_m, gives a greater weight to the humidity index I_h = 100 S/PE than to the aridity index I_a = 100 D/PE, indicating that water surplus in one season may to a certain extent compensate water deficit in another.

In an adjusted system (Thornthwaite and Mather, 1955), the procedure for computing the water balance was changed, increasing the assumed moisture holding capacity of the profile from 100 mm to 300 mm, related to vegetation and soiltype, and introducing a different function for soil moisture depletion during a dry period. Humidity index and aridity index are now given equal weight, so that,

$$I_m = \frac{100\ S - 100\ D}{PE} \qquad (3.2.)$$

with a range of -67 to -33 for the semi-arid areas. Although frequently referred to, the accuracy of Thornthwaite's classification system is restricted and not very satisfactory for semi-arid tropical regions (Barry and Chorley, 1976).

Another, less complicated, technique for classifying climatic areas is described by Troll (1965). His approach is based on the duration of the humid season. For this, a month is defined as humid if the mean precipitation exceeds mean potential evaporation. Semi-arid areas are defined as thorn savannah belt (dry semi-arid) if the number of consecutive humid months is 2 to 4½, or dry savannah belt (wet and dry semi-arid) with 4½ to 7 humid months.

Hargreaves (1971) defined a moisture availability index (MAI) based on estimated potential evaporation and amount of rainfall expected at a 75% probability level of exceedance, based on monthly values,

$$MAI = \frac{P\ (75\%)}{PE} \qquad (3.3.)$$

with: P (75%) = Amount of precipitation exceeded in 75% of the cases (mm/month).

PE = Mean potential evaporation (mm/month).

Three or four consecutive months showing a MAI exceeding 0.34 define a semi-arid climate, in which the production of crops with 3 to 4 months growing period is possible.
For a further delineation of the tropical areas of India and the world, ICRISAT has selected Troll's classification. Potential evaporation is computed by Penman's method (Penman, 1948). This methodology requires a simple base data set, available for a large number of locations.
Figure 3.1. shows the semi-arid areas of India, based on this classification, differentiating between the "wet and dry" semi-arid zones and the "dry" semi-arid zones. Following this methodology, however, some areas of the west and the east coast are included that would be better classified as humid or sub-humid (Krishnan, 1980).

From an agricultural point of view the crucial characteristics of a semi-arid area are its aridity for the major part of the year and an annual potential evapotranspiration that exceeds annual precipitation (Sanchez, 1976). The occurrence and level of rainfall is only just sufficient for growing good crops which makes the semi-arid areas a special case in agricultural research and management. From this it appears that, using Troll's classification, semi-aridity should be limited to areas experiencing 2 to 4½ humid months as is also done by Krantz (1981). The areas with 4½ to 7 humid months, indicated as "wet and dry semi-arid" should then be classified as semi-humid or subhumid, with different agricultural potentials and problems.

A shortcoming of Troll's classification system seems to be that a month is generally too long a period to consider for its humidity or aridity. If looked at from the point of availability of water for crop growth, a humid period adds water to the rooted soil-profile, which acts as a moisture storage system. During an arid period the crop uses (part of) this stored water. Within both the periods defined as humid or arid wet and dry intervals occur, that replenish and dessicate the soil-profile respectively. Total net quantity of water that goes into storage during wet periods also depends on the available profile storage capacity and on the infiltration characteristics of the profile, so that, apart from the rainfall distribution, intensities of rainstorms are also important parameters that determine the actual moisture storage. The length of a standard period should, therefore, also be related to percentage infiltration, the moisture buffer capacity of the rooted soil profile and the water requirement of the crop. Higher crop available profile storage capacities and better infiltration would increase the length of such a period. For red soils, with a profile water retention capacity of about 100 mm, this period should probably not be more than about two weeks.

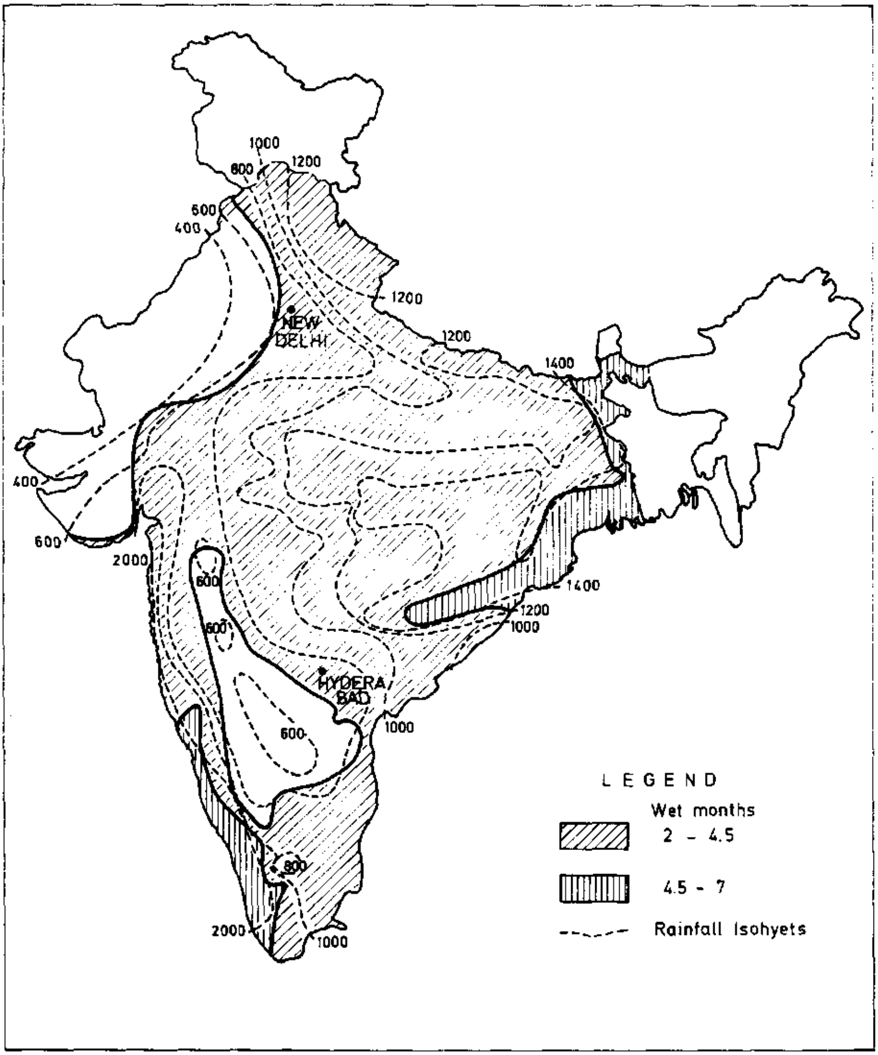


Figure 3.1. Semi-arid tropical areas in India (shaded areas), according to Troll's classification.
Adapted from ICRISAT (1980a)

The different systems of classification mentioned above are all oriented towards crop water availability rather than on single parameters like temperature or precipitation. As the availability of water is a complex system, not only based on climatic factors but also on other factors like soil, vegetation and management, it is clear that even such systems are bound to be general in nature. Local variations in for example profile depth would never divert that location to a different climatic group, although such variations are very important for the local producers.
In this perspective, this study should also be seen: although, as a generalization, it is delineated to a semi-arid tropical environment, its applicability ought to be evaluated in a farmer's field.

3.2. Description of the Red Soils

The red sandy soils around Hyderabad, India, belong to the order of Alfisols, with associated Entisols and Inceptisols. These and similar soils are widespread in semi-arid tropical environments. They are developed from pink granites, granitoid gneisses, quartzites, sandstones etc. and are characterized by a high percentage of coarse and fine sand particles (Rajan and Rao, 1978). The clay in these soils is predominantly the kaolinitic, non-swelling type. The depth of the A-horizon varies from only a few to 30 cm and has a sandy loam or loamy sand texture, sometimes stony. In Alfisols a hard and clayey B-horizon (argillic horizon), red to dark red in colour at varying depth and of varying thickness occurs, underlain by a gravelly disintegrated rock subsoil, in India known as "murrum". Entisols and Inceptisols lack such strong horizon development (IRRI, 1974). Moisture content at saturation amounts to about 20% vol., and 8% vol. at permanent wilting point. The total depth of the profile varies strongly, partly due to the high levels of erosion that have occurred in many of the Alfisol areas. The profile water retention capacity varies, in arable land normally from 75 - 125 mm, sometimes lower than 75 mm, generally not higher than 150 mm (ICRISAT, 1978). The soils are moderately well drained with reasonable hydraulic conductivity. The pH ranges from 5.5 to 7.0. Alfisols are low in all bases, usually low in nitrogen, phosphorus and sometimes zinc. Potassium-level is usually medium to high. As in all red soils cation exchange capacity ranges from 10-20 m.e./100 g for medium deep soils but is less than 10 m.e./100 g for shallow ones. Organic carbon percentage is low (Sastry and Mathur, 1972; Virmani *et.al.*, 1976). Appendix 1 shows typical profiles of a shallow and medium deep Alfisol respectively, at the research station of ICRISAT.

The red soils cover the largest area of the semi-arid tropics (Sanchez, 1976). Apart from India these soils are found in semi-arid regions of many other countries, like Angola, Brasil, Cameroun, Chad, Dahomey, Ghana, Mali, Nigeria, Sudan, Togo, Burkino Fasso (formerly Upper Volta), Zambia, etc. (Cocheme and Franquin, 1967). In semi-arid tropical India alone there are about 70 million hectares of them (Raychaudhuri and Rajan, 1963; Kampen, 1975), covering more than 40% of the semi-arid tropical regions in the country. If one estimates the percentage of cropped area of the Indian red soils at 70 *(Section 3.3.)*, this would amount to an area of 50 million hectares.

Apart from the most sandy parts, red soils are too hard when dry to cultivate with animal traction. If cultivated with the help of a tractor, the topsoil tends to pulverize or break-up into large and hard clods. In moist conditions, however, the management of these soils is easy.

The sandy and silty nature of the topsoil gives rise to a low stability of the aggregates. Wetting and the impact of raindrops disintegrate surface aggregates easily. This disintegration strongly affects the movement of water. Firstly, it decreases the surface roughness, thereby reducing the surface depression storage capacity, the effect of which is discussed in Chapter 6 in more detail. A second effect of this disintegration is a reduction of infiltration through the easy formation of a surface crust.

As an explanation of this process, fine material is thought to be loosened and washed into surface pores, reducing their volume, whereas raindrop impact compacts the toplayer. A further reduction of the permeability may take place by the deposition of suspended material after the rain has ceased (McIntyre, 1958 a), aggrevated by suction forces which arrange the soil particles at the soil-atmosphere interface in a dense packing (Morin *et.al.*, 1981). The resulting crust, therefore, consists of two distinct layers (McIntyre), being a thin skin seal of oriented clay and silt particles, according to Tacket and Pearson (1965) of about 0.1 mm and a washed-in region of varying depth. Rawitz *et.al.* (1981) at this point differentiate between a crust and an underlaying cemented layer. Evidently, the presence of a crust reduces the potential infiltration rate of the surface, a value frequently referred to as "infiltration-capacity", but rightfully defined by Hillel (1974) as the "infiltrability" *(Section 5.1.)*. This reduction was measured by Kirkby (1980) to be at least by a factor ten. Several factors can be mentioned which influence the density of the formed crust. Outstanding among them are the kinetic energy of the rainfall reaching the soil surface and soil-characteristics like texture, structure-stability and moisture content, although the precise relations between them are not entirely clear (Gerard, 1965; Tacket and Pierson, 1965; Lemos and Lutz, 1957).

Crust formation not only has a negative effect on the infiltration but the hardening of the toplayer also affects the ease and the quality of subsequent intercultivations. Moreover, if a hardening of the toplayer occurs immediately after the seeding operation, this may hamper emergence. Looking at it in this way, Klay (1983) concludes that, in general, crust formation under the Indian semi-arid conditions seems much less of a problem than in most African areas. This difference could both be attributed to the more vulnerable soil in Africa and to the occurrence of higher intensity rainstorms (Hoogmoed and Stroosnijder, 1984).

3.3. Common Cropping systems

Forty-two percent of India's geographical area is used for permanent cultivation (Goverment of India, 1979). For the semi-arid parts of India this percentage is much higher and in many of the semi-arid districts the cultivated area amounts even to 70 - 90% of the geographical area (Randhawa and Venkateswarlu, 1980). This does not necessarily mean that all of this area can be considered as suitable for permanent production, but the high population density in this part of the world and the low production levels force the inhabitants to use every possible piece of land for food production.

Common crops are the ones that are grown for own consumption or the local market in the first place, followed by cash crops if they have a high relative gross margin[+)] compared to the food crops, like some oil-seeds. In the red soils, crops are grown during the monsoon season ("kharif"), possibly extending into the post-monsoon season, making use of residual moisture. The choice of crops thereby depends on soil quality, soil depth and rainfall characteristics. Common foodgrains grown in the red soil areas of semi-arid India are "jowar" or sorghum *(Sorghum vulgare)*, "bajra" or pearl millet *(Pennisetum typhoideum)*, "raji" or finger millet *(Eleusine corocana)* and a number of minor millets *(Setaria* spp.). These crops have a reasonable level of drought resistance, which is even better for the millets than for sorghum. As the latter is preferred by the farmers, it is common practise in drought prone areas to grow a mixture of sorghum and millets both at

+) "gross margin" is defined as the production value minus variable costs.

full plant population. Depending on the actual rainfall of the season one of the two crops will produce the best yield.

Apart from the foodgrains, pulses and oil-seeds are grown in the red soil areas. Of the pulses red gram *(Cajanus cajan)* green gram *(Phaseolus aureus)*, black gram *(Phaseolus mungo)*, horse gram *(Dolichos biflorus)* and cowpea *(Vigna catiang)* are the most common. The important oil-seed-crops for red soils are groundnut *(Arachis hypogaea)*, sesame *(Sesamum indicum)*, rape *(Brassica napus)*, mustard *(Brassica nigra)* and castor *(Ricinus communis)* (Arakeri, 1962).

The most important crops grown under rainfed conditions on the red soils of semi-arid India and their gross average yield are listed in table 3.1. The last column indicates their relative importance for rainfed production. The table also shows the importance of food grains and pulses, occupying 75% of the total cropped area of India. Crop choice is also related to farm size.

The smaller the units, the more the cultivators tend to grow for their own consumption. Small farmers also have a significantly higher extent of intercropping than large farmers (Jodha, 1981). And last but not least, the farmer needs a produce of fodder for his cattle. The level of production balances around the farmer's own minimum food requirement and often stays below this.

Table 3.1. Important rainfed crops in red soil areas of semi-arid India and their yields.

Crop	Gross Average Yield		Percentage Rainfed
	kg/ha		%
	(1)	(2)	(3)
Sorghum	730	840	80
Pearl Millet*	430	510	80
Finger Millet*	1090		60-70
Small Millets*	440		100
Red gram	720	670	90
Other grams	660		90
Groundnut*	840	790	90
Castor*	350		90
Sesame*	210		90

* Crops mostly or exclusively grown on red soils

Sources:
(1) Derived from Government of India, Reference annual (1979)
(2) Quoted from Kanwar (1980)
(3) Randhawa and Venkateswarlu (1980)

In the semi-arid areas of India, the land/man ratio amounts to 0.67 person per hectare on a geographical basis. Distribution of sizes of operational holdings is given in table 3.2. for India as a whole and for the semi-arid states. The skewed distribution of the holdings is evident. The high land pressure, which is still increasing and the sub-optimal environmental conditions (soil and climate) do not allow for more than subsistence farming for most operational units. Input levels are bound to be low as most farmers are not in a position to save and invest to improve their agricultural system or even part of it.

More often than not crops are grown in intercropping systems. Under conditions of rainfed farming at subsistence level, the growing of crops in mixtures matches the available resources in maintaining low but relatively stable production (Andrews and Kassam, 1976). In low and uncertain rainfall areas the yield advantages of mixtures over sole crops can often be explained by a difference in water-use pattern over the growing season of the component crops, so that part of the mixture makes the best use of the actual moisture availability of a particular season. In higher rainfall areas intercropping may allow for a better utilization of space and time (Andrews and Kassam).

Sanchez generalises the reasons for intercropping systems being more productive as follows (Sanchez, 1976):
- a better utilization of available solar radiation;
- higher efficiency in utilizing soil or fertilizer applied nutrients;
- fewer problems with weeds, pests, and disease control;
- better use of available manual labour and other low-energy technology.

Table 3.2. Size distribution operational holdings.

	INDIA		SAT-states	
Size class	households	area	households	area
(ha)	(%)	(%)	(%)	(%)
< 0.2	36+)	0.3	35+)	0.2
0.2 - 0.4	6	1.0	4	0.7
0.4 - 1	16	5.6	15	4.6
1 - 2	16	12.3	15	10.4
2 - 4	14	20.7	15	19.7
4 - 10	9	31.2	12	31.1
10 - 20	2	17.3	3	20.1
> 20	1	11.6	1	13.2

+) About 80% of this group might be considered as landless
Adapted from Ryan et.al. (1975)

Among other reasons, the preference for mixed cropping could also be directed by the wish of the farmer to grow all elementary crops for his own consumption or by the need for crop adaptation to local differences in his field. In this respect, a differentation can be made between the following systems:

- *mixed intercropping:* different crops, broadcasted or row-planted, are sown, managed and harvested simultaneously;
- *row intercropping:* different crops are sown simultaneously, but in distinct rows. Cultivation of the different crops might vary slightly, harvest differs in operation and generally also in time;
- *strip intercropping:* different crops are grown simultaneously in strips, wide enough to permit independent cultivation, but narrow enough for the crops to interact agronomically;
- *patch intercropping:* different crops are grown on different patches in the same field. Sowing, cultivation and harvesting is done independently;
- *relay intercropping:* a second crop (or crop combination) is planted between a standing crop (or crop combination).

The difference between these systems is not always distinct. Moreover, the farmer may use combinations of the above mentioned systems.

Systems of sequential cropping are not very common in the red soils, except in situations where (supplemental) irrigation is available. Ratooning of crops (the cultivation of crop regrowth after harvest) is sometimes practised in situations of heavy drought injury to a standing crop.

Mean production figures *(table 3.1.)* are low due to poor production factors, erratic rainfall makes even this low yield uncertain. Although the figures for smaller regions or individual fields will come out much higher, for SAT-India as a whole, the co-efficient of variation of yields for sorghum is 9.4%, for the millets 22.2%. This higher variability of millet-yields is directly related to the fact that they are primarily grown in areas with lower average annual rainfall, where consequently the probability of drought is much higher (Ryan and Binswanger, 1980).

Use of chemical fertilizer in rainfed agriculture is low. Of the total Indian fertilizer use, which increased from 16 kg/ha in 1973 - 1974 (Agrawal, 1980) to an average of 31 kg/ha in 1979 - 1980 (Tandon, 1981), nearly 80% was used for rice, wheat, sugarcane and cotton, mainly irrigated crops. More than half of the Indian farmers do not use fertilizers at all (Tandon). Most farming households are already in debt (Arakeri *et. al.*,

1962) and cannot afford more credit in view of the risk of crop failure if rains do not support the standing crop. Moreover, the local varieties generally used for the foodgrains, do not have the high yield potential as modern varieties have. A shift to modern varieties with chemical fertilizer, however, would require a more stable production environment and technology in respect to crop protection, factors most small and marginal farmers can not guarantee. Fertilization, therefore, in most rainfed food grain production is restricted to the use of farm yard manure. However, of the total production of dung not more than 18-30% is used as manure (Sopher, 1980), with a strong preference for cash crops (castor, groundnut), which means, that for the foodgrain production only marginal quantities of farm yard manure remain available.

For land preparation, sowing and intercultivation locally manufactured implements, drawn by bullocks or buffalo's are commonly used. Use of tractors is almost entirely concentrated outside the rainfed SAT-areas (Binswanger, 1978). Depending on soil type, rainfall pattern and anticipated crop, different tillage-systems are used (Rastogi, 1980).

In the red soils, where cereals are grown in monoculture or in combination with pulses, sowing is done as early as possible, i.e. immediately after the first good rain, wetting the profile to a depth of about 30 cm, around the beginning of the monsoon. Primary tillage is in some areas restricted to two or three passes with a so-called blade-harrow after the occurrence of a pre-monsoon shower. In other cases a ploughing operation, with wooden or iron ploughs is done every year or in alternate years. Cash crops, like castor and groundnut, are generally planted somewhat later, to gain time for a better primary tillage and to be more sure of continuing rains. Use of indigenous seed-drills is common, or otherwise a technique is used in which the seeds are put into a small furrow by hand, and earthed with the next pass of the plough.

Intercultivation for weed control and breaking of the crusted topsoil is done with a blade-harrow one to three times during the early part of the growing season. In addition to this, one handweeding might be done in the cash crops. Use of herbicides in rainfed crop production in semi-arid India is negligible, mostly because the present weed control practices appear to be adequate under the present cropping system (Shetty, 1980).

To deal with the unpredictability of the rainfall, be it a delayed onset of the monsoon, prolonged dry spells, or an early cessation of the rain, and to avoid complete crop failure "drought strategies" are recommended

(Krishnamoorthy *et.al.*, 1974; Singh, 1977). These recommendations, to be adopted for individual regions, would include suggestions for a change of crop or crop-variety, thinning to reduced plant stand and ratooning of the standing crop *(see Section 4.4.)*.

3.4. The Water-component: Availability, Drainage, Irrigation

The relatively low water retention capacity of red soils and the erratic distribution of rainfall in the semi-arid tropical regions cause uncertainties in moisture availability and therefore make rainfed agriculture unstable and risky. Length of the growing season is determined by the duration of the rainy season, supplemented with the period in which crops can fulfill their transpiration requirements from profile stored water. The lower the mean rainfall and the shallower the profile, the higher is the probability of drought injury during the growing season, for a certain crop. In that case, the moisture in the profile becomes limiting to adequately support the crop for its transpiration needs during an interval of insufficient rainfall. This problem is also related to the seasonal rainfall distribution *(Section 5.2.1.)*. On the other hand, sufficient profile storage capacity could counteract the adverse effects of a too dry period in situations where earlier more abundant rainfall could have been stored. Complete crop failure, however, caused by moisture shortage, is not uncommon in parts of India, especially not in a number of areas that for that reason have been officially indicated by the government as "drought-prone".

Whereas water can be a problem because of its scarcity at one moment in the season, it may be excessive during another as a consequence of long duration and/or highly intensive storms, resulting in ponding and surface runoff. High intensities of rainfall also act destructively on the soil surface aggregates, resulting in a hardening and sealing of the topsoil. This process by turns might reduce the infiltration, particularly in depressions where sedimentation of fine particles is concentrated. Runoff can cause great damage to the fields because of related soil transport and washing out of organic matter and nutrients. In the red soils, although sandy by nature, stagnation of water for one or more days may occur. In agricultural fields, where depressions are of such size and shape that the plants are located in them, this waterlogging may directly or indirectly adversely affect the crop. Moreover, insufficient drainage prohibits the farmer from entering the field for some time.

Irrigation could secure the water availability and as such stabilize and increase the agricultural production in the semi-arid zones. The red soils are suitable for most irrigated crops, with the possible exception of rice, because of the high percolation losses. However, while at this stage, irrespective of soil type, about 25% of the cultivated area in India is irrigated (Randhawa and Venkateswarlu, 1980) and a further development of irrigation is foreseen, the maximum area that can ever be covered will never exceed 40-50% of the cultivated area of India (Sarma, 1982), so that at least half of India's agricultural fields will always remain dependent on the local precipitation as the only water source.

In semi-arid tropical zones with a secure but limited availability of irrigation water, it would seem obvious to use this for supplementary irrigation of upland crops. Yields of crops could be secured through small watergifts, bridging periods of drought, which would create an important increase in average yield. Experience in India has shown however, that, whenever irrigation water was made available, the cropping pattern changed to high-valued crops, even in situations where the system was originally designed for protective irrigation of upland crops. This is caused by a combination of technical and non-technical factors and strenghtened by the difference in pay-off between upland and irrigated crops (Anonymous, 1962, cited by Jodha, 1978; Krishnamoorthy *et.al.*, 1974), resulting in an uneven distribution of the available water over the command area, in favour of the head-enders (Malhotra, 1984).

A similar controversy can also be seen in the traditional tank-irrigation systems, common in South-India. Surface runoff water is collected and stored in reservoirs from which lower fields are irrigated, but this is mainly for rice production. Water use could be as high as 1,000 mm per cropping cycle (Agrawal, 1980) or even more under poor management systems, a volume of water that could serve at least a tenfold area, if used for supplementary irrigation of rainfed crops.

These examples show a less than optimal use of the scarce production factor, water, at least from the point of view of food crop production. It is clear that, in such situations, an overall improvement of crop production could be attained by better management of the available water. How this can be achieved depends on a number of factors, that include the physical condition of the area, the availability of techniques and the level of organisation. In subsequent chapters a number of such factors are described in more detail to try and give a better idea of the problems and possible solutions related to the water availability under the conditions of rainfed agriculture in the semi-arid tropics.

CHAPTER 4 WATER MANAGEMENT SYSTEMS IN ARID AND SEMI-ARID AREAS

4.1. General

The terms "dry farming" and "rainfed farming" in (sub) tropical areas are interchanged by many authors and are generally not well defined. Both terms are frequently used simply to distinguish from irrigated farming, without giving them a clear meaning. "Dry farming" is sometimes defined (ICRISAT, 1979) or implicitly used (Arnon, 1972) as a system of agriculture in arid areas made possible by conservation of water *in situ*, by a technique of water harvesting or runoff diversion. Other authors use the term "rainfed" for conditions where mean annual precipitation exceeds a certain critical amount, depending on the climate, above which non-irrigated agriculture is more or less stable, using the term "dry land" for non-irrigated locations with lower rainfall, and consequently undependable yields. Ten Have (1977), for example, refers to a limit of 800 mm of mean annual precipitation for tropical areas with summer rainfall to be exceeded for practising rainfed agriculture. To allow for dry farming, Wallen (1966) and also Ten Have set the limit at 500 mm for areas with summer rainfall and 250-300 mm for areas with predominantly winter rains.

A common characteristic in all definitions of dry farming and rainfed farming is that they both depend on precipitation rather than irrigation for water supply and that varieties of crops are grown that have a low yield response to water deficit, compared to the high producing varieties grown under irrigated conditions that are also most sensitive in their response to water (Doorenbos and Kassam, 1979). Yet, a distinction between the two could be made on the basis of the expected sufficiency of local precipitation to raise the crop without additional water. Where a system of dry farming is used, agriculture would have been unproductive or even impossible in most of the years without one of the special dry farming techniques as for example fallowing alternate years, as practiced in the Great Plains, (Greb *et.al.*, 1967), runoff farming as in Tunisia (Amami,

1979) or *agricultural water harvesting*, well-known in ancient and modern Israel (Evenari *et.al.* 1971), i.e. techniques through which more water is made available to the crop than is received by it from rainfall on the occupied area during its growing cycle. On the contrary, in rainfed farming systems some level of crop production is possible in most years without such import of water. This still implies that water shortage could be a reason for poor yields or even crop failure in single years and that application of water in addition to infiltrated rain would generally increase production.

According to this differentiation, dry farming systems are to be practiced in arid regions, rainfed farming systems in the semi-arid and wetter areas.

4.2. Systems of Water Diversion and Collection

Since historical times, people have made use of surface runoff, lead by natural conditions to locations where the water could be used for agriculture. But man-made constructions intended to divert runoff are also age-old, as are techniques to increase runoff from catchment areas for subsequent use.

Shortage occurred where there was a need for water in excess of the local precipitation, which could not be replenished by other sources, like a river. In some locations the quantity of local precipitation was too low for human existence, in other areas a concentration of water enabled a strong economic development.

Activities oriented at water diversion and collection can be split up according to technique and specific objective. A useful separation in systems could be made, which depends on whether or not a technique is used to:

- induce runoff in the catchment area;
- divert the runoff to a selected area;
- store the water in excess of profile retention.

With these differentiations in mind, the following systems can be defined:

Water harvesting: A system of inducing runoff by treating a catchment area (Myers, 1975). In historical lay-outs the runoff is diverted to a storage reservoir and mainly or exclusively used for human consumption or as drinking water for their livestock.

Another water harvesting system, referred to as the system of *Agricultural Water Harvesting* or *Micro-Catchment*, on which much research has been done in recent years (Boers and Ben-Asher, 1982) concentrates on runoff inducement in small plots or strips. There, the runoff concentrates at one side of the plot or strip, infiltrates and directly contributes to the available moisture in the rooted profile of an individual productive shrub, tree or crop row.

Runoff farming, or water spreading: A system in which runoff water from a treated (Myers) or untreated (Lawton and Wilke, 1979) catchment area is directly diverted to - or held back in - lower located agricultural fields, each runoff event serving as a water-gift.

Runoff collection: A system aiming at collection and storage of precipitation in excess of infiltration mostly from productive areas, with the aim of using this water at a later stage as supplementary or full irrigation in the same or a different area, mostly nearby the location of storage. Runoff collection is classified by Lawton and Wilke as a water conservation rather than a water harvesting technique.

Other systems

Among other systems, floodwater farming makes use of the runoff concentrated by natural watersheds in a river system, that overflows at times of high discharge, sometimes flooding huge areas in floodplains or deltas. The water may be kept impounded for some time by constructing earthen dams around the fields. Such areas are rich in clay and fertile by yearly deposition of suspended material and crops are grown on residual moisture, often supplemented by groundwater. The difference between runoff farming and floodwater-farming lies in the fact that in the former system a more or less clearly defined, relatively small and possibly treated area contributes water at each runoff producing occasion, while in the case of floodwater-farming the contributing area is supposed to be much larger, untreated and remote.

An important system with the emphasis on water diversion is the "chain of wells", better known as "qanats". This system dates back to 1,000 B.C., but a great many of them are still in use today in countries like Iran and Afganisthan, where they are a very important water supply to the dry but fertile valley lands. Vertical head wells into the water bearing layers of an alluvial fan collect water that is subsequently transported through a gently downward sloping underground tunnel to a lower point on the surface.

A series of vertical shafts connecting the tunnel with the ground surface act as ventilation and entry for maintenance (Nat. Acad. Sci. U.S.A., 1974; Kuros, 1984). Inasfar as qanats provide a more or less permanent flow of water, not directly dependent on the local precipitation, their use can be classified as irrigation farming, which distinguishes them from the systems mentioned earlier, that are characterised by an uncontrolled water availability.

4.2.1. Water Harvesting

Water harvesting systems are always based on runoff inducement in the contributing area. Historically, such systems were developed in arid areas where annual rainfall quantities were too low for any settled form of existence. In the Negev-desert, underground cisterns have been found for storage of harvested water for consumption, dating back to 1,000 B.C. (Evenari *et.al.*, 1971). Clearing of the contributing area of stones and construction of stone strips is seen by Evenari as a technique used to increase the runoff efficiency, which is the collected runoff as a percentage of rain.

In recent research projects modern techniques and materials are used in an attempt to accomplish the same (Fink *et.al.*, 1980). Starting from the simplest activity, Hillel (1974) indicates five techniques to induce runoff from an area:

- eradication of vegetation and removal of surface stones, also to permit the formation of a crust;
- smoothing of the catchment area, to reduce the stagnation of water in depressions;
- compaction of the top layer, to decrease infiltration;
- dispersion of soil colloids with sprayable solutions of sodium salts, to induce crusting;
- impregnation of the surface with sealing and binding materials (sprayable petroleum products) to create a water repellent and stable coating.

The purpose is to avoid stagnation of water in micro-depressions and to decrease infiltration in the area. Both intend to lower the threshold retention, i.e. the amount of precipitation needed to initiate runoff (Fink *et.al.*, 1979). The soils of the northern Negev-region, prove to be specifically suited for water harvesting, because of their loamy nature with a high pH- and ESP-value, factors affecting the aggregate stability negatively and favouring crust-formation. The importance of this is made clear by Rawitz and Hillel (1971) who found that the distribution of rainfall intensities for this area is strongly skewed towards lower values, a condition otherwise unfavourable for water-harvesting.

4.2.2. Agricultural Water Harvesting

The system of agricultural water harvesting, more commonly referred to as micro-catchments is also based on the inducement of runoff. It differs from water harvesting, however, in respect to the application of the harvested water (which is restricted to agricultural use), the size of individual catchment areas (which are small, serving the water needs of individual trees (Evenari, *et.al.*, 1971), shrubs (Fink and Ehrler, 1979) or crop rows (Gardner, 1975)) and consequently in respect to lay-out, as agricultural water harvesting does not require any diversion, transport facility, silt trap or storage of water.
Runoff efficiency is much higher than for the larger catchment areas used in water harvesting lay-outs, for which the figures, given by Shanan and Tadmor (1979), are indicative *(table 4.1.)*.

A differentiation, according to lay-out, can be made (Shanan and Tadmor) between:

- Catchment basin, with an individual plot size, depending on mean precipitation, of up to 200-300 m^2, serving the water needs of a single tree or shrub.
- Runoff-strips, where water collects from one or two sides in the line of a row crop with a ratio of water contributing area to production area of 4 : 1 to 20 : 1.

Table 4.1. Annual runoff related to area of catchment in Negev-desert: annual rainfall 100 mm

Size of Catchment Area	Average Annual Runoff
(ha)	(mm)
< 0.02	10 - 30
5 - 10	4 - 10
300 - 500	1

Derived from Shanan and Tadmor (1979)

Treatment of a catchment area requires a high input in lay-out and maintenance and costs of water are consequently high (Oron *et.al.*, 1983). Runoff efficiency can be increased by the use of dispersion agents or impregnation of the surface in the catchment area, but a glance at the costs involved, as given by Frasier (1975) shows the impractibility of a wide application. For many years to come, their usage will be restricted to small, developed locations, for growing high valued crops, like fruits and vegetables.

4.2.3. Runoff Farming

In runoff farming crops receive runoff water from adjacent treated or untreated areas. The individual fields are usually small, may be located in natural catchment areas and may be enclosed by borders to contain and conserve the water (Lawton and Wilke, 1979).

Runoff farming and flood control are very much related approaches in arid and semi-arid areas, as both are oriented at constructing systems that intercept (excessive) runoff. A runoff-farming system forces the water to contribute to crop growth instead of letting it drain out of the area. Water spreading systems as described for Pakistan (Nat. Acad. Sci. U.S.A., 1974), and the contour-bund system widely applied in India (Rama Rao, 1974), both serve purposes of flood control and water conservation be it that in the latter case an emphasis is laid on the flood- and erosion-control and that the water, as far as possible is kept in place rather than diverted to a different area.

In arid regions the water is always lead to a receiving area which is much smaller than the contributing part. Evenari *et.al.* (1971) describe the individual terraced wadi's and the runoff farms of a size up to 5 cultivated hectares, which are surrounded by barren hillsides from where water is diverted for direct watergifts. Of the 100 ancient runoff farms studied, the average ratio of catchment area to cultivated area was 20. In India, similar systems existed in West-Rajasthan, called "khadi", dating back to the 15th century (Kolarkar *et.al.*, 1983).

A modern runoff farming system (Jones and Hauser, 1975) is the conservation bench terrace, originally developed by Zingg and Hauser (1959). Levelled contour benches, constructed with a terrace ridge to keep water impounded, receive runoff water from a contributing area that is kept at the original landslope. Actual dimensions depend on slope, soil, land use and anticipated runoff. This system looks very similar to that of runoff strips described in section 4.2.2., but differs in the fact that the catchment area is not treated to induce runoff, so that it should not be considered as a water harvesting system.

4.2.4. Runoff Collection

Contrary to water harvesting, runoff collection is a passive system in as far as inducement of runoff is concerned. The runoff contributing area is left for its original use, and excess rain is generally allowed to follow the natural drainage path. At a location suitable for the purpose, a valley or depression is closed by an earthen or masonry dam, which creates a reservoir or "tank". The objective of this is mostly to enable the growth of irrigated crops, that have a high relative yield advantage over rainfed upland crops, especially where the latter are grown in shallow soils or in regions with low rainfall.

Runoff collection and storage are meant to concentrate water on an areal basis and transfer it in time. In India, on average about 17% of the total irrigated area is served by tanks (Singh, 1974). In individual districts this figure may be much higher, especially in the southern states. Most tanks are in the smaller size range. Ludden (1978), for a district in Tamil Nadu State, mentions 2,000 out of 2,500 tanks as smaller than 40 hectares, this figure being the average size. Out of 41,000 tanks in the state Karnataka, with an average command area of 21 hectares, 16,000 serve an area of less than 4 hectares (Sundar and Rao, 1982).

Storage involves high percolation and evaporation losses and reservoir dimensions are chosen to secure a maximum stored quantity, spilling excess runoff water in few years. The production efficiency of the runoff water, in terms of the percentage of the runoff water that ultimately becomes available for tranpiration by a crop, is low.

In traditional lay-outs the use of collected water is commonly restricted to irrigate rice downstream of the reservoir (Sharma and Helweg, 1982; Doherty, 1982), a water demanding crop with a high economic and social value. Application of water can easily be done by gravity, length of conveyance channels is restricted and soils are best in the valley bottoms.

Yet, in well-managed runoff collection systems upland crop production can also benefit from it, if the silt deposits, removed from the reservoir bottom to maintain its capacity, are returned to the fields of the catchment area. Such techniques, traditional for many parts of Southern India (Sopher, 1980) can be seen as a symbiosis between rainfed farming in the catchment area and irrigated crop production in the valley.

However, many (especially small) tanks have fallen into disuse (Von Oppen and Subba Rao, 1980). The decay of the tank irrigation systems should at least partly be seen in the changes in organisational structure that have occured since India's independance. Before 1947 many of the smaller tanks were the private property of powerful individuals and the society was organised by a strong dependancy of agricultural labourers on this local elite. Changes in property rights and social dependancies since then seem to have been instrumental in a decline of many of the tank-irrigation systems. The poor farmers preferred the cultivation of a small piece of rainfed land, that they had acquired as their own, to continuing to depend on the land owners in an unfavourable tenant-like situation in the irrigated area (Doherty, 1982). In other situations, the management of the tank system was entrusted to public bodies that were not supplied sufficient budget to properly maintain the system.

4.3. Techniques of in situ Water Conservation

There are also techniques that are oriented at the *in situ* conservation of water that is in excess of direct infiltration and surface retention. These differ from the previous systems in as far as they do not envisage diversion or prolonged surface storage. Their aim is to hamper the surface flow of excess water and to prolong the time available for infiltration, thereby reducing the runoff component of the area in question.

This can be attained by the system of *tied ridging*, which aims at keeping all or part of the excess water near the crop, by damming created furrows at regular intervals (FAO, 1966). Another approach follows the construction of so-called *contour-bunds*, which are earthen dams, located at regular height intervals, that are laid out on the contour hooked up with side-bunds. Such contour-bunds are similar to "level terraces", "ridge type terraces" or "absorptive type terraces" (Gupta *et.al.*, 1971). Surface runoff water stagnates behind these bunds up to a level that is fixed by a spillway.

Both techniques of tied ridging and contour-bunding are frequently used in semi-arid tropical regions, the former mostly in Africa, the latter in India. They will be dicussed in more detail in Chapter 6.

4.4. Crop Management in Semi-Arid Tropical Agriculture

In the absence of the possibility of supplementary irrigation the need arises to practise agriculture on the basis of techniques that maximize the rainfall use efficiency, defined by Kampen (1975) as the agricultural production in relation to annual precipitation. Gardner and Gardner (1983) remark that, to combat the effects of drought in rainfed agriculture, agricultural solutions might well be the best in the long term, where engineering solutions become more and more expensive or otherwise unacceptable.

In India, research on rainfed farming systems started as early as 1926 (Basu, 1954). In 1970, the All India Co-ordinated Research Project for Dryland Agricultural (AICRPDA) was established by the Indian Council of Agricultural Research (ICAR) comprising 23 research centres and representing different soil and climate regions in India (Krishnamoorthy *et.al.*, 1974). In these centres special emphasis is given to the development of techniques of farming and to the selection of suitable crops, crop varieties and crop combinations, including their fertilization and tillage requirements. Many of the recommendations tested by these centres are derived from early work done at the Sholapur dry farming research centre, which resulted in the so-called "Bombay dry farming method" (Rama Rao, 1962; Joshi *et.al.*, 1980), recommending deep ploughing, contour bunding, field levelling, manuring, contour cultivation, the use of wide row spacing, limited plant density and several intercultivations. The impact on productivity, however, was marginal due to the unavailability of suitable genetic material that would better match the rainfall pattern (Singh, 1982).

More recent advice, therefore, includes the use of such improved varieties of drought escaping or drought resistant crops and chemical fertilizers, stressing the need for proper weed control and good sowing methods. Even then, "drought strategies" are important to deal with the consequences of an unpredictable rainfall pattern. Ruthenberg (1976) compiled a number of recommendations that were earlier given by Krishnamoorthy:

- If the onset of the rains is delayed then other varieties, crops, crop mixtures, seed rates, and fertilizer applications have to be chosen.
- If gaps in rainfall (during the humid season) occur, then the capacity for re-sowing should be available, weeding has to be done more carefully, ratooning of millets and sorghum can be practised (the first growth is cut as fodder and the ratoon crop produces the grain) and fertilizer application has to be split.
- If the rains stop too early, then moisture demanding plants of the crop mixture ought to be removed; the crop of maize and sorghum may be saved by removal of the lower leaves.

What these recommendations have in common is, that they are all based on the condition of easy availability of inputs like labour and capital, which, however, will generally not be the case with the majority of small farmers.

4.5. Appraisal of Water Management Systems for Red Soils

In arid and semi-arid tropical regions a major direct constraint for optimal crop production in most years, is the availability of water. In arid regions it is availability as such, in semi-arid tracts it is more often availability in time, mean seasonal precipitation being basically sufficient. Development of rain depending systems that increase crop production, therefore, should be oriented at water diversion towards restricted areas (water harvesting systems) in the arid parts and at optimal *in situ* water utilization in the semi-arid parts, a differentiation that coincides with that of dry farming and rainfed farming *(section 4.1.)*.

Runoff farming and agricultural water harvesting, typical dry farming techniques, increase the average quantity of available water in the cropped area, but its variability remains high. The systems will even have a higher variability of water inflow (rain plus diverted runoff) as would occur in their absence, because runoff percentage usually increases with rainfall. As the variability of precipitation is already appreciable, such systems are only effective if the profile water retention capacity is sufficiently high to store the incidently large amounts of water received. This makes these systems suitable for restricted areas of deep and clayey soils.

In the semi-arid tropics the higher mean precipitation provides sufficient water on a seasonal basis for an adapted crop in most years, thus eliminating the need for additional inflow. There, as far as the availability of water is concerned, the distribution of rainfall is more significant than its total, at least, if a set minimum amount occurs (Morin and Matlock, 1974). In other words, water availability is a problem of irregular distribution rather than seasonal shortage. It cannot be solved by increasing the amount of inflow, if the system lacks storage capacity. However, if sufficient capacity is available, as in the case of the deep Vertisols in India, simple *in situ* water conservation through monsoon-fallowing already permits the growing of a so-called "rabi"-crop (post-monsoon season crop) on this stored water. This system, therefore, is independent of the distribution of the earlier rains.[+)] This is obviously not the case for crops grown during the rainy season.

The sandy and often shallow red soils, however, lack the storage capacity to allow the cultivation of post-monsoon crops or to benefit from a system providing additional inflow. Therefore, a system of *in situ* water conservation and subsequent cropping would not be practical to escape the effects of the variability of rainfall. For the same reason, water conservation through contour-bunding can also not counteract the irregular distribution of rainfall: excess water concentrates in only a minor part of the cropped field where the small profile water storage capacity will soon be filled, but still be insufficient to support crop growth during a subsequent drought. Tied ridging in red soils might be useful up to some (easily reached) point of profile water saturation, but neither will be able to conserve enough moisture to bridge long dry spells.
Considering this, the only useful alternative for red soils under these climatic conditions is a lay-out that enables collection of excess water in surface reservoirs or ponds during wet periods, using this water for supplementary irrigation during dry spells.[°)] Understandably, such system will only work when the reservoir has had sufficient inflow before the moment water is required. Such inflow stems from watershed runoff, which depends on a large number of variables, like actual rainfall, management practices and on characteristics that are intrinsic to the particular catchment.

+) Although this approach of water conservation is traditional for extended areas of deep Vertisols in India, proving to be workable within the climatic conditions and farmers' constraints, important disadvantages are high soil loss rates and a low precipitation efficiency. Therefore, such systems should be abandoned in favour of adapted monsoon-cropping systems (Anonymous, 1981).

°) This does not exclude the need to firstly try and replenish the soil profile and to reduce unproductive water losses from the profile (section 6.1.).

To get an idea of the applicability of this approach, profile water balances were calculated, based on actual rainfall, measured runoff and assumed values for evaporation and transpiration *(Appendix 2)*. The calculation was made for two levels of (assumed) profile storage (PS). Whenever the profile was saturated, any additional infiltration was considered as being lost by percolation to deeper layers.
The resulting lines of available water in the soil profile and the cumulative runoff, potentially available for storage, are shown in figures 4.1. - 4.3. These refer to an Alfisol field of 0.4 ha (RW-3H) and for the years 1979 through to 1981. In the figures, periods of crop water stress, as defined in Appendix 2, show clearly. It appears, that the inadequacy of shallow profiles (those with PS = 75 mm) to hold the infiltrated water, results in higher percolation losses and an earlier profile depletion as compared to deeper profiles *(figure 4.1.)*. Consequently, in terms of alleviating stress periods, crops grown on shallow profiles would benefit most from additional water gifts during the growing season.

As far as the potential for water collection is concerned, the variability of runoff over the years is considerable. In a relatively dry year like 1979 *(figure 4.2.)* and without any runoff during the first 100 days or so, a runoff collection system would not be of any help. But in most years, runoff can be expected even during the early part of the season. The wet year 1981 *(figure 4.1.)* actually shows a high amount of runoff in the first half of the season, followed by a stress period. In other years, however, (1980, *figure 4.3.)* runoff is present, but the quantities involved are small. This stresses the need for careful collection and use of this water. In such situations the behaviour of fields or areas as related to their size can be of considerable importance. Comparing the cumulative runoff from a 0.4 hectare field and a neighbouring 4 hectare subwatershed, experiencing the same rainfall, the higher runoff level from the smaller area is clear *(table 4.2.)*.

Table 4.2. Observed runoff (mm) from similarly treated 4 ha watershed and 0.4 ha field (mean figures of two areas both) during the period June till October, for three years.

Year	Precipitation (mm)	Runoff (mm)	
		4 ha watershed	0.4 ha field
1979	660	90	90
1980	720	80	110
1981	1.000	180	240

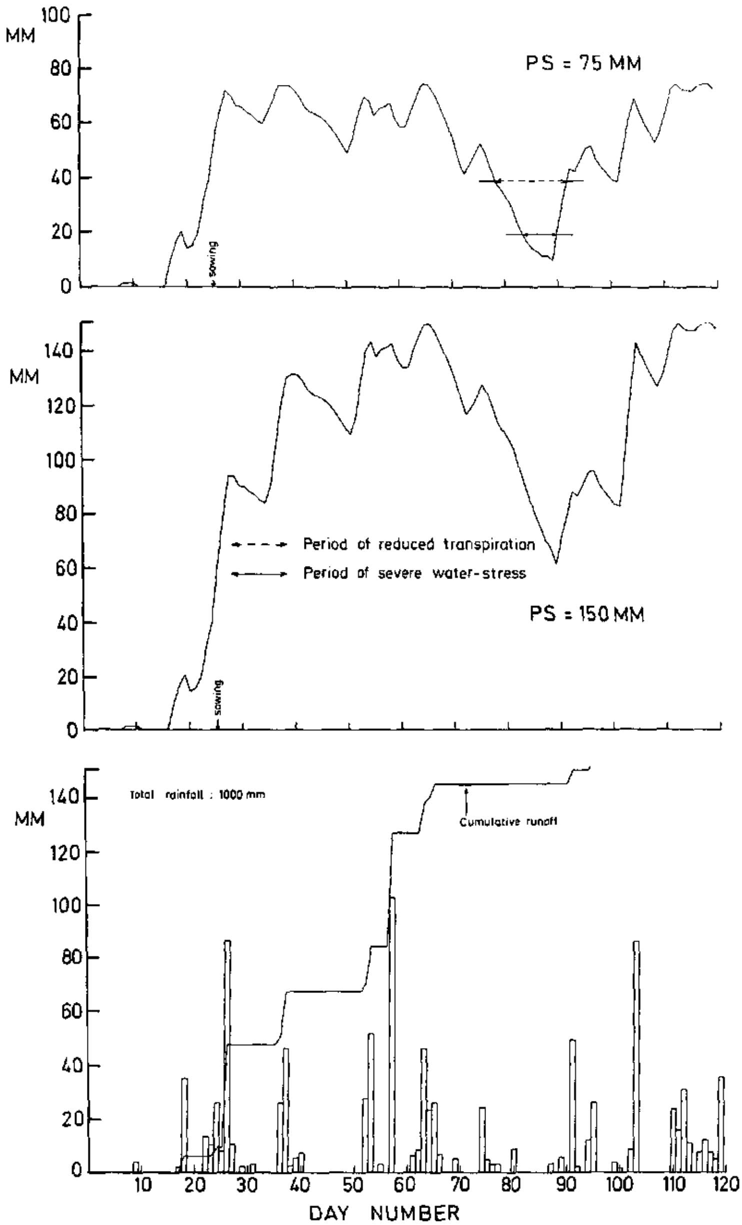


Figure 4.1. Calculated available moisture for profiles with storage capacity (PS) of 75 mm and 150 mm respectively (June-September, 1981).

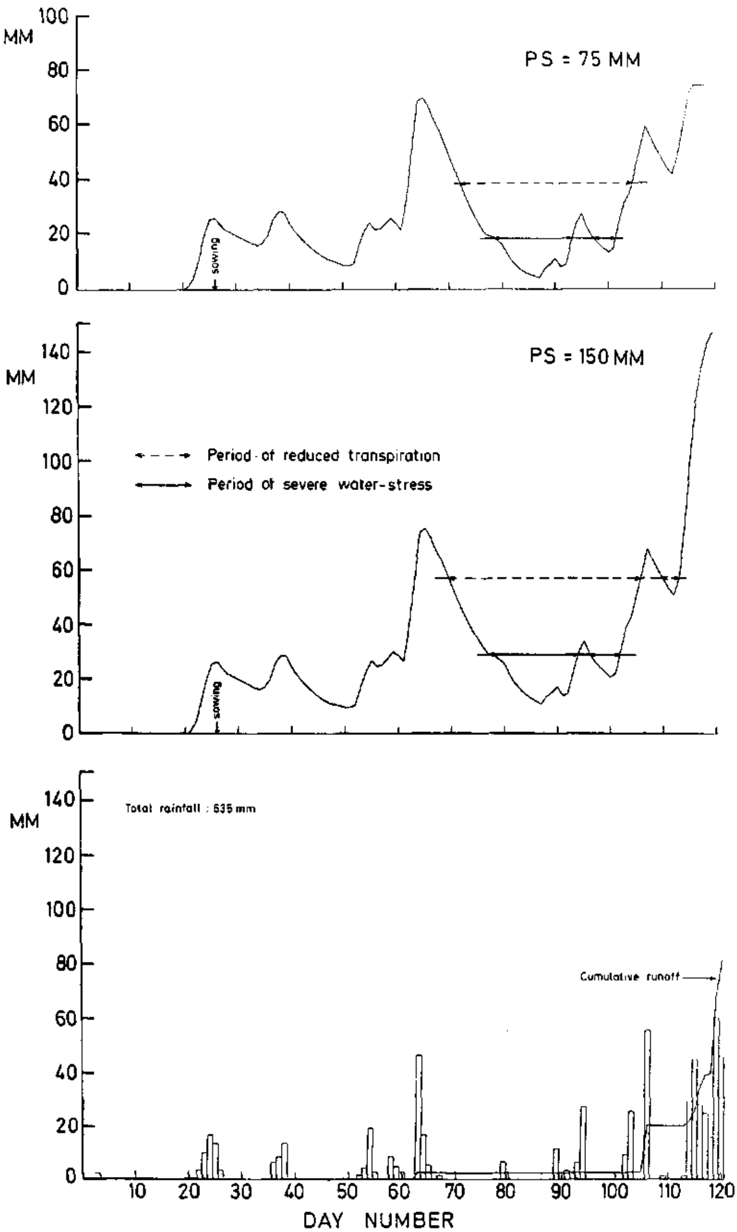


Figure 4.2. Calculated available moisture for profiles with storage capacity (PS) of 75 mm and 150 mm respectively (June-September, 1979).

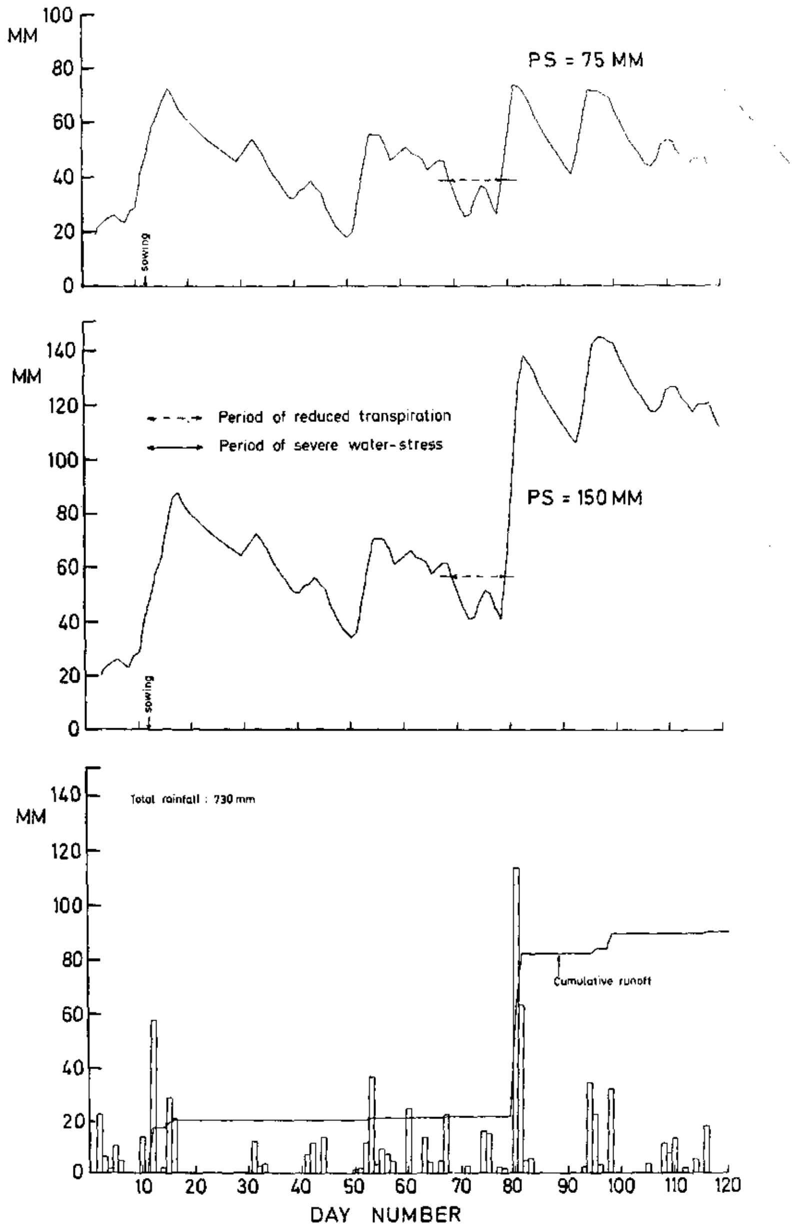


Figure 4.3. Calculated available moisture for profiles with storage capacity (PS) of 75 mm and 150 mm respectively (June-September, 1980).

CHAPTER 5 THE WATER MOVEMENT IN RAINFED AGRICULTURE

5.1. A Flow Chart for Water Movement

The single primary source of water in rainfed agriculture is the local precipitation. As we restrict ourselves in this study to the tropical regions, we can assume that transport and storage will always take place in the liquid or vapour phase.

The geographical area under investigation is restricted to small agricultural watersheds, as defined in section 2.8., deprived from the possibility of recovering groundwater for agricultural use. Deep drainage and percolation of water, therefore, are considered as losses in the water balance. Import of water as source of supplemental irrigation is not considered. Apart from negligible quantities of dew, the input is the local rainfall only.

Figure 5.1. is a simple flow chart, indicating the water movement in such a rainfed agricultural system with surface water collection and re-utilization, under the restrictions given above. Its objective is to indicate the general relation between precipitation and the crop available moisture, which is the water temporarily stored in the soil profile as far as it can be used by the crop for transpiration.

Precipitation
Precipitation falls in storms of different sizes and intensities and at unpredictable times of occurrence *(section 5.2.)*. These factors, together with particulars of the crop including its growing stage, infiltrability of the profile, topography and land-management factors, define the way the water moves.

Interception
After the rain has ceased, part of the precipitation remains on the vegeta-

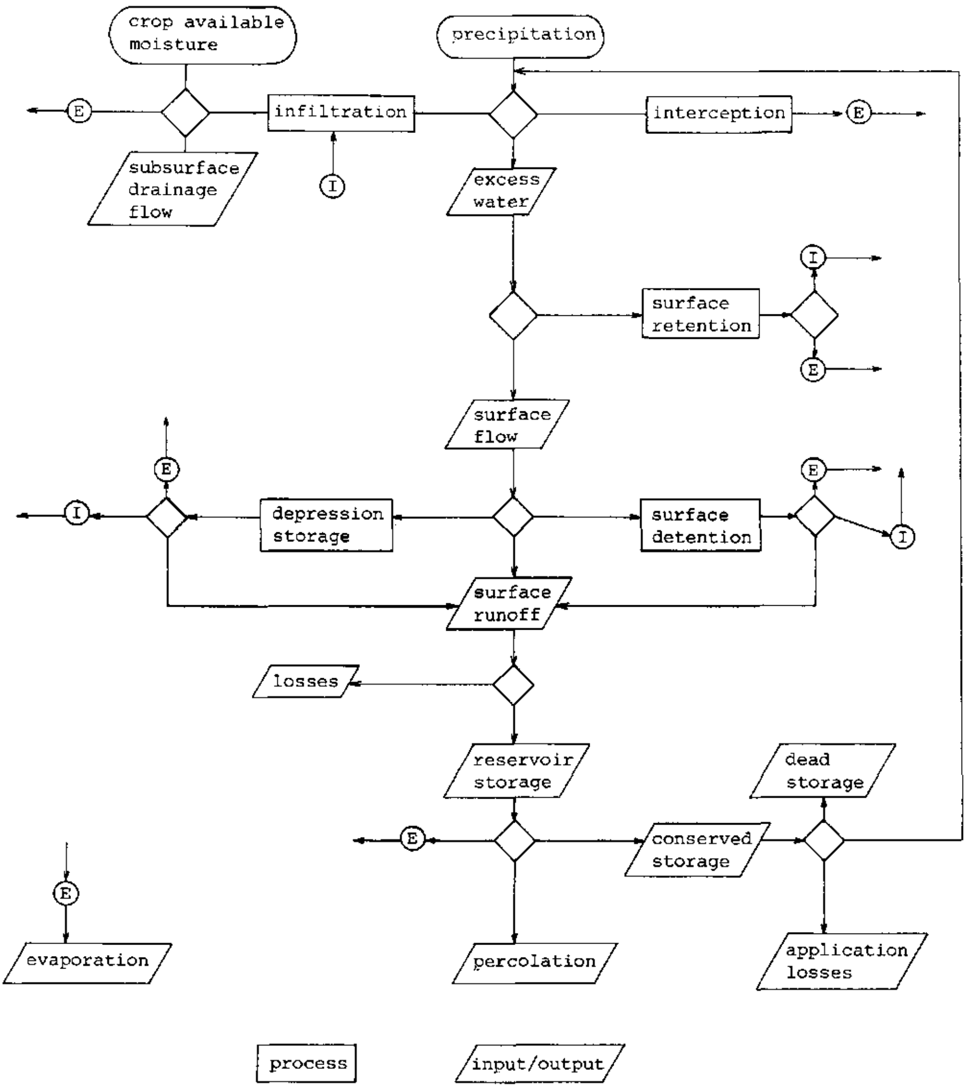


Figure 5.1. The water movement in a rainfed agricultural system.

tion surface and on organic mulches and residues lying on the soil surface. This amount is known as interception. The total quantity of interception is of course strongly dependent on the percentage and density of crop cover and the presence of a litter layer. At crop establishment stage the interception by the crop cover is still negligible. But even with a fully developed annual crop the quantity of water retained will be restricted to a few millimeters only. The intercepted water will drip or evaporate from the surfaces (Blake, 1975). Interception can have a large influence on the water balance of forests (Linsley, 1949), especially in climates with frequent rains of low intensity. For annual crops it is less important and can be described as a simple subtraction of the total quantity of precipitation in the early stage of a rainstorm. It has no significant influence on the intensity of precipitation reaching the soil surface, but may strongly reduce the kinetic energy of the raindrops. Through this latter effect interception may help in maintaining the infiltrability of the soil profile by protecting the topsoil-structure.

Infiltration

The precipitation that reaches the soil surface will partly or completely infiltrate into the soil profile. The maximum rate at which the water enters the soil at a certain time is fixed by the infiltrability, defined by Hillel (1974) as the infiltration flux when water at atmospheric pressure is made freely available at the soil surface. This means that:

$$I_a = P_r \quad \text{if} \quad P_r < I_{max} \qquad (5.1.)$$

$$I_a = I_{max} \quad \text{if} \quad P_r \geq I_{max} \qquad (5.2.)$$

with I_a = Actual infiltration rate (mm/h)
P_r = Precipitation rate (mm/h)
I_{max} = Infiltrability (Maximum infiltration rate) (mm/h)

The infiltrability is determined by the texture and structure of the soil, and its moisture content *(section 5.3.1.)*, showing a variation over short and longer periods of time within the growing season. The infiltrated water adds to the profile-storage which is the reservoir from where a growing crop will take the water required for transpiration.

Losses from Profile

Part of the water held by the top layer of the profile, however, evaporates under the influence of the energy-influx at the soil-surface.
Another sink may be formed by weeds, that directly compete with the crop for transpiration.

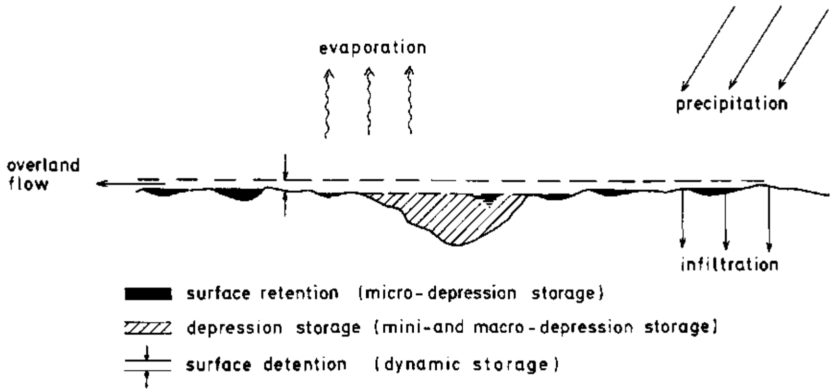


Figure 5.2. The water balance at the soil surface: retention, detention and depression storage.

Water infiltrated in excess of the maximum profile storage capacity cannot be held and will, under influence of gravitational forces, move downward, leaving the area from where roots could possibly extract it. This water, considered as deep drainage, will add to the groundwater reserve, locally or, after horizontal transport, elsewhere. In the studied situation, deep drainage of water, when not regained by capillary rise, is a loss-factor.

Surface Retention and Depression Storage

If the intensity of precipitation at any moment exceeds the infiltrability of the profile, excess water will start building up on top of the soil surface. Gravity will force this water to move, following the local slope. Part of this water, however, will immediately be trapped in micro-depressions, which are closed drains, formed by fresh or weathered surface aggregates and organic material *(figure 5.2.)*.

This phenomenon is known as the surface retention of water or micro-depression storage *(table 5.1.)*.

After the local micro-depressions are filled to capacity, excess water will start to flow. Not all of this water will leave the area considered as part

Table 5.1. The different levels of depression storage

	typical horizontal distances	examples
micro-depressions	1 - 10 mm	depressions formed by aggregates
mini-depressions	10 - 50 cm	tied furrows, implement marks
macro-depressions	> 1 m	topographical depressions, contourbunds

of it could be caught in larger depressions within the cropped field.

In this study, a further differentiation is made between mini- and macro-depressions *(table 5.1.)*. Mini-depressions, often purposely created or maintained and mostly located outside the crop rows, have such a size that they will remain present during the crop growth unless intentionally removed. Macro-depressions will either be of natural origin, formed by topographic undulations, or purposely created to restrict field outflow. They have a more permanent character, cover a much larger area than mini-depressions and consequently do interfere with the growing crop.

While depressions are filled up during periods that rainfall intensity is in excess of infiltrability, the reverse process starts whenever rainfall intensity falls below the infiltrability of the profile. Emptying of depressions through infiltration continues after cessation of rain. Part of the water stored is also removed by evaporation.

Surface Flow and Surface Detention

While, during a period of rainfall excess, the micro-depressions are filled up, surface flow in the field begins. This water, moving as free water over the soil surface, will start filling up mini- and macro-depressions, if present, while an increasing part will contribute to the outflow of the field. This process goes to the point that all available depressions are filled to capacity and additional excess rainfall is moving towards the drainage channels. This volume of moving water, producing surface runoff, is known as surface detention (Horton, 1940). After the rainfall excess is over and consequently the source of overland flow stops, part of this surface detention will continue to create runoff, while another part may infiltrate.

Surface Runoff

Surface runoff is that part of the excess rain that ultimately leaves an area as free flowing water. One must distinguish between field runoff and watershed runoff, the latter being a combination of fields with a common drainage channel. Per unit area, field runoff always exceeds watershed runoff, and the difference may be considerable. In natural conditions, surface runoff is lost as a source of water for crop production or any other purpose in the area of origin.

Reservoir Storage

Construction of reservoirs makes it possible to collect and store surface runoff and utilize it at a later date. If the location of the reservoir is at some distance downstream, the net inflow of the reservoir equals outflow of the field or fields minus losses, caused by water stagnation and infiltration in the connecting waterways.

Reservoir Losses
Losses during storage consist of evaporation losses and percolation losses, which are related to reservoir characteristics, climatic conditions and time. In addition, losses may occur through transpiration by emerging or floating aquatic weeds. Of the water remaining at the time it is required for irrigation, part is not recoverable from the reservoir, the so-called dead storage.

Available Water
Part of the original precipitation is directly available for the crop; from any excess at best only part can be conserved for irrigation at a later stage of the season through collection of runoff and storage in reservoirs or from recovery of groundwater. In the area described only the first method is feasible.

Distribution of rain and storm intensities are the major uncontrollable variables. Topsoil condition could be controlled to some extent and much of the reservoir losses could be avoided but only at high costs.
The available water in the reservoir could be transported to a (cropped) field. As in all irrigation, application losses occur at this stage.

5.2. Rainfall Characteristics of Hyderabad, India

The semi-arid tropics have a monsoon-type of climate with a dry season in winter and a wet season in summer. Characteristics of the wet season, as starting time and duration, amount, distribution and reliability of rainfall, may restrict the crop choice or limit its yield potential under rainfed conditions (Webster and Wilson, 1966). The relations between monthly values of potential evapotranspiration and rainfall are used to provide guidelines for the climatic suitability of a location for certain types of rainfed agriculture *(section 3.1.)*.

Mean annual rainfall in semi-arid tropical India as a whole, a summer rainfall area, varies roughly from 500 to 1,200 mm[+)]. Figure 3.1. *(chapter 3)*

+) Values derived from Krishnan (1975), table 2: "Moisture, Aridity Indices and Seasonal Distribution of Rainfall in Semi-Arid Regions". In winter rainfall areas, semi-aridity occurs at much lower amounts of rainfall. Winter rains, however, are more common for subtropical and temperate regions.

shows the rainfall isohyets of the Indian subcontinent. The variability over the years, however, is high. The coefficient of variation is 20 - 30% (Virmani *et.al.*, 1980b) with a higher value for the drier areas (Jones *et.al.*, 1981). The mean annual precipitation for Hyderabad, India, located at 17°27' N and 78°28' E at an altitude of 545 meters, is around 760 mm, with measured extremes of 320 mm (1972) and 1,400 mm (1917) during the period of observation *(figure 5.3.)* and a coefficient of variation of 26%.

Dependable precipitation, defined by Hargreaves (1975) as the amount of rainfall having a specified probability of occurrence, for Hyderabad amounts to 400 mm/year at a 75% probability level. For the growing season, calculated from June 1st to October 1st, this figure is about 350 mm.

5.2.1. The Rainfall Distribution

The rainy season in India is confined to the period from April through to October. In general, the ratio of rainy season rain to annual rain is related to the latitude of the location (Krishnan, 1975). For Hyderabad (latitude 17°27' N) this value is 88%. Rainfall occurring outside the rainy season is generally of no practical use, as storm sizes are too low to increase the soil moisture reserve. Incidentally a good wetting of the top soil before April would enable a tillage operation.

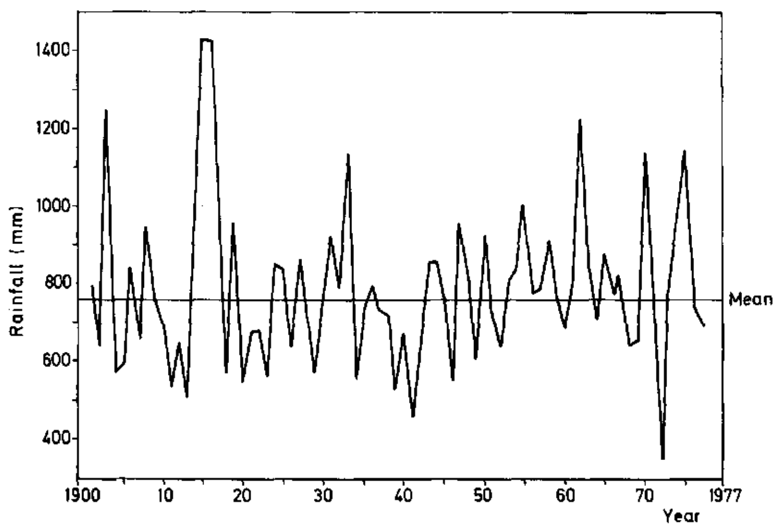


Figure 5.3 Annual rainfall at Hyderabed, India; 1901-1977.
Derived from Virmani et.al. (1980b).

The rainy season, as opposed to the dry season, is the period in which at least some useful precipitation can be expected. This definition is based on the expectation that at some point in the early part of the rainy season rains will exceed and subsequently continue to exceed the actual evaporation losses from the bare soil (Webster and Wilson, 1966), so that the crops can be sown and seedlings may survive. As the transpiration of a newly established crop remains low for some time, due to their restricted leaf area (Dancette and Hall (1979)) and likewise, crop water requirements at the end of the growing season are low again due to ripening, the rainy season can be indicated as a period that starts earlier and ends later than the period defined as humid. It includes a part or all of the pre-monsoon season, the monsoon season and the post-monsoon season. During the former, Hyderabad receives 11% of the total annual rainfall, whereas 77% falls during the latter two. In some years, however, precipitation in the pre-monsoon season might be partly conserved, if water penetrates the profile below the layer contributing to direct evaporation *(section 6.1.)*.

During the monsoon potential evapotranspiration rates drop sharply, due to the decrease of solar radiation and temperature. The start of this humid period is uncertain and could deviate up to four weeks from its mean date (Arnon, 1972). Monthly mean potential evapotranspiration rates stay below the mean amounts of rainfall *(figure 5.4.)*. Considering shorter periods

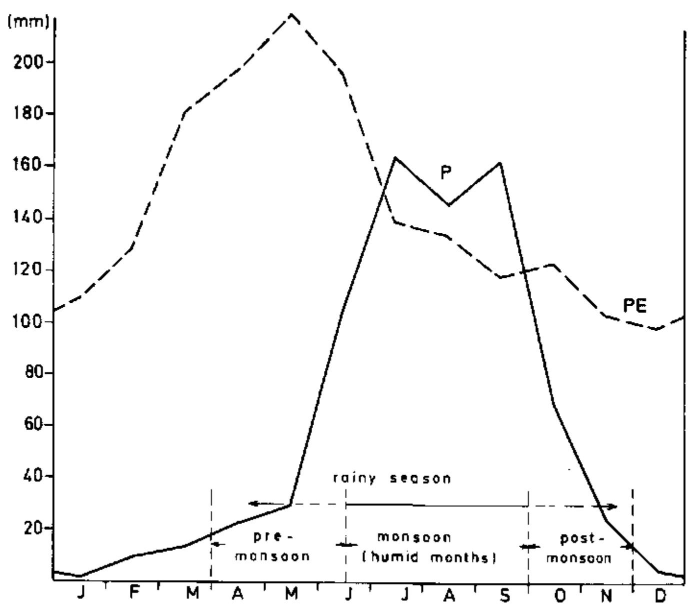


Figure 5.4. Precipitation (P) and potential evaporation (PE); monthly means for Hyderabad, India.

within this humid period, this is not necessarily true, and most locations in India are even characterized by the occurrence of a dry spell in August. Yet, such a relatively short dry spell is still considered as part of the humid season (Jackson, 1977). The seasonal distribution of rain for Hyderabad is illustrated by the 3-week moving average rainfall *(figure 5.5.(a))*. Again, a dry spell in mid-August is clearly shown. The frequency of occurrence of different storm size intervals on a weekly basis is given in Appendix 2, whereas the percentage contribution of different storm sizes to total rainfall, in 3-week moving periods, is graphically indicated in figure 5.5.(b).

The figure shows an increasing representation of bigger size storms in the course of the humid season. While, for example, 40% of the rainfall in the early weeks of the humid season occurs in storms of over 20 mm, this is about 60% by the end of September at a similar total rainfall figure. Storm sizes are important parameters, as, on the one hand very small storms are hardly effective for crop growth and most water will evaporate directly without contributing to soil moisture and crop transpiration, while on the other hand bigger storms may give rise to high runoff percentages and erosion.

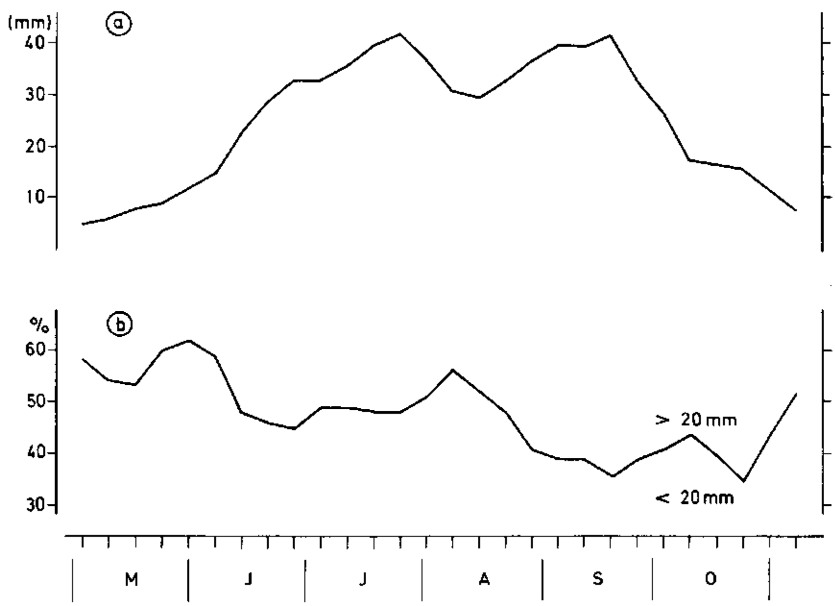


Figure 5.5. The seasonal distribution of rainfall as 3-week moving averages for Hyderabad, India. (a) Weekly rainfall. (b) Percentage contribution of storms smaller than 20 mm to all rain.

5.2.2. Intensities of Rainstorms

The intensity of a rainstorm is defined as the amount of precipitation per unit of time and is generally expressed in mm/h. It is an important parameter in the water movement. If the intensity of rainfall at a certain moment exceeds the infiltrability of the profile, excess water may lead to runoff and transport of soil. Moreover, the intensity of a rainstorm determines its kinetic energy. High kinetic energy may result in severe aggregate destruction, surface compaction and soil splash.

Most storms can be divided into intervals with more and less intense rainfall. Intervals with a high rainfall intensity will, to a large extent, characterise the erosivity of the storm. Particularly during these intervals the kinetic energy reaches its highest levels.+)

Intensities of rainstorms are, therefore, often expressed on the basis of intervals of 5, 10, 15, 30 or 45 minutes. Intensities of storms are then given as the maximum precipitation during any such interval within the rainstorm.

A storm can also be identified by its Weighed Mean Intensity (W.M.I.), defined as

$$W.M.I. = \frac{1}{P} \sum_{i=1}^{n} P_i \cdot I_i \qquad (mm/h) \qquad (5.4.)$$

with P_i and I_i the rainfall and its intensity respectively for each of n intervals. The intervals are chosen as periods of constant intensity as read from the rainfall charts. Characteristic for this expression is the inclusion of the total storm size, P.

If related to runoff, (particularly with the unstable red soils), this expression gives a more accurate description of a storm, as the runoff producing character of a storm does not heavily depend on the extreme intensity of its intervals *(Chapter 6)*.

+) An estimate of rainstorm energy, E_k, can be made with the help of an empirical formula as developed by Wischmeier (1958):

$$E_k = 11.9 + 8.73 \log I \qquad (MJ \cdot ha^{-1} \cdot mm^{-1}) \qquad (5.3.)$$

with I = Rainfall intensity in mm/h.

The erosivity of the total rainstorm is subsequently defined as the product of total rainstorm energy and the maximum 30-minutes intensity. This yields the EI_{30}-index, which in many situations has been proven to give a good correlation with observed soil loss (Hudson, 1971).

In tropical regions, intensities of rainstorms could be high. As an illustration for Hyderabad, maximum rainfall intensities for 15 minute periods, that exceeded 40 mm/h were recorded on three dates in 1977 and on eight dates for each of the three subsequent years. Figure 5.6. shows the values of rainstorm sizes and their weighed mean intensities of a number of runoff producing storms during the 1981 season, which were obtained from detailed analysis of rainfall charts. Neither for these data, nor for other years, could a correlation be detected between the size of a storm and its weighed mean intensity.

5.3. The Profile Water

5.3.1. Infiltration of Red Soils

Infiltration is the downward movement of water into the soil-profile. This term refers to the cumulative quantity of water that enters a unit cross-section during a certain period of time (I_{cum}). The quantity of water that can infiltrate under ponded conditions per unit cross-section in a unit of time is defined by Hillel (1974) as the infiltrability. It is the infil-

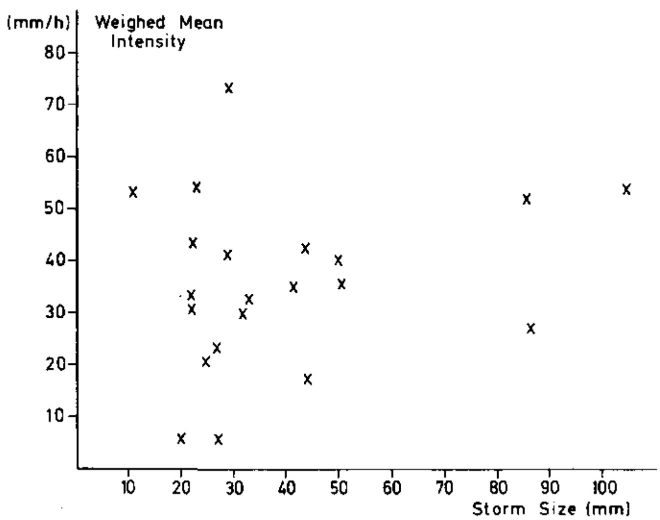


Figure 5.6. Storm sizes versus their weighed mean intensities for 21 rainfall events (ICRISAT station, RW-3, gauge 3).

tration flux density, when water is made freely available at the soil surface and at atmospheric pressure

$$I_{inst.} = \frac{dI_{cum}}{dt} \qquad (5.5.)$$

This value decreases with increasing profile moisture content up to a constant value at saturation (I_f), inherent to the texture, structure and density of the soil. The general shape of an infiltrability curve for an initially dry soil shows a high value at the moment water application starts, followed by a more or less sharply decreasing interval and approaching a constant value - the final infiltration rate.

Profiles with layers of different texture or structure are non-uniform and have a final infiltrability determined by the vertical saturated conductivity of the horizon with the lowest permeability, assuming that no horizontal flow occurs. Moreover, sharp boundaries separating horizons will act, upon wetting, as a barrier for water transmission under unsaturated conditions.

Profiles of most red soils are inhomogeneous. Alfisols are characterized by an argillic B-horizon whereas the Entisols are stratified due to their layerwise deposition (IRRI, 1974). Spotwise variability is high through erosion and sedimentation over the years, influencing the depth of the A-horizon. Infiltration measurements, therefore, are always biased, as no location can be selected which is representative for a larger area. Other general errors encountered in infiltration measurements are lateral subsurface flow and the fact that water is applied as a layer on the surface. On the one hand, this induces a hydraulic pressure hardly present during rainfall. On the other hand it might promote air entrapment, which reduces the infiltration rate.

The problems of lateral flow and local variability can partly be solved by choosing a larger area for the infiltration measurements and by surrounding this area with a buffer-zone. At ICRISAT, square metal frames of size 1.5 x 1.5 m are used for this purpose, with a second frame of 2.44 x 2.44 m placed around it, creating a buffer-zone of about 45 cm (ICRISAT, 1976). Figure 5.7., line 1, shows the measured infiltrability of an Alfisol profile against time, using such infiltration frame.

Tricker (1978) studied the accuracy of single ring infiltrometers. To compensate for lateral flow, he measured total wetted volume and wetted volume below the cyclinder in laboratory experiments. This enables the

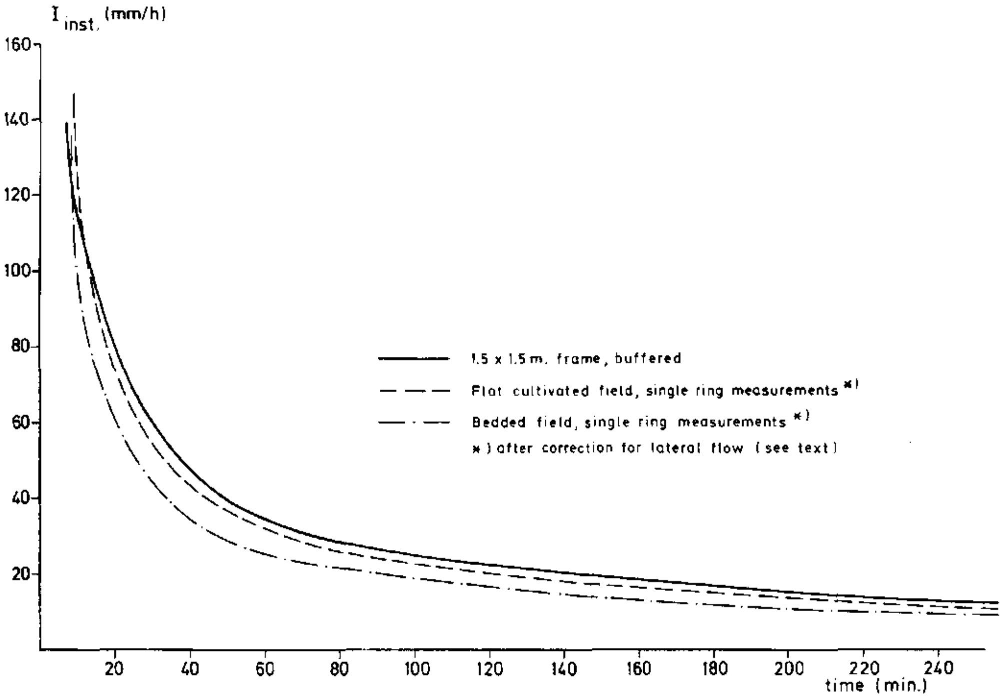


Figure 5.7. Infiltrability of Alsifol profiles at ICRISAT station (RW-3F).

calculation of the true vertical infiltration, assuming the same moisture content all over the wetted volume of soil, through:

$$f_c = f_m \cdot \left(\frac{V_c}{V_t}\right) \qquad (5.6.)$$

With: f_c = corrected infiltration (cm/h);
f_m = measured infiltration (cm/h);
V_c = wetted volume below cylinder (cm^3);
V_t = total wetted volume (cm^3).

A multiple regression analysis based on his experiments resulted in the equation:

$$\log f_c = 0.46 \log f_m - 0.64 \log t + 1.08 \quad (R = 0.98) \qquad (5.7.)$$

where log = decimal logarithm, and
t = time from beginning of infiltration (min).

With additional measurements he showed that the use of this equation as correction procedure would yield outcomes, rarely deviating more than 20% from real values, even for layered soils. Deviation of measured values from true infiltrability decreased when using larger size cylinders. A cylinder diameter of 15 cm was recommended as a further increase hardly reduced the error of measurement.

Lines 2 and 3 in figure 5.7. show the infiltrability of an Alfisol based on a number of such 15 cm-cylinder measurements, corrected according to Equation 5.7. Measurements were done in the tilled area as well as in the traffic area of both bedded and flat cultivated fields; each object had four or five replicates. Individual infiltration values were corrected according to the described regression equation and are listed in appendix 4. The lines 2 and 3 in figure 5.7. were composed of the mean values of the two zones, giving double weight to the measurements in the tilled zone, which covers approximately double the area compared to the traffic zone. As can be seen the resulting lines correspond reasonably well with the much larger infiltrometer frames (line 1), which evidently supports the use of single rings for practical reasons.

Compaction of the traffic zone reduces infiltrability. At all times, measured infiltration rates in the traffic zone were about 40% lower than in the adjacent tilled area *(Appendix 4)*. This difference proved to be highly significant. Figure 5.8. depicts this situation for the corrected infiltration-cylinder measurements. The overall effect of the reduced infiltrability of the traffic zone might be even stronger as excess water tends to collect in this part of the field, specifically in the case of a bed-and-furrow surface configuration.

The infiltration measurements discussed so far are executed by applying a layer of stagnant water on top of the soil surface, which, as already mentioned, is not representative of the conditions occurring during rainfall. In the experiments the full surface area was constantly exposed to the water. Moreover, compaction of the topsoil due to raindrop impact did not occur, which otherwise leads to reduced infiltration.

Small plot experiments of a size of 2 by 1.5 meter, described in Appendix 11, which were sprinkled at an intensity of about 18 mm/h, showed a large variation in mean infiltration rates, but were never higher than 16 mm/h. Instantaneous infiltration rates dropped to a value of about 7 mm/h within 90 minutes after initiation of rainfall. Such figures seem far more realistic under field conditions: Rainstorms with an intensity of 20 mm/h mostly result in runoff, although the infiltration curves of figures 5.7. and 5.8. would indicate that this would almost never occur. This discrepancy, also described by Langford *et.al.* (1970), concentrates on the initial stage of wetting, and is mainly caused by the effects of aggre gate breakdown under rainfall impact (Ellison, 1945). Entrapped air (Jarrett and Fritton, 1978), influences infiltration in the opposite direction, but at a different rate. More often than not, initial infiltration rates, measured by flooding techniques yield higher values than those obtained through measurements with simulated rainfall.

Final infiltration rates, however, are much less sensitive to the methodologies used. In earlier measurements this final rate for Alfisols was already found as 7.7 ± 3.7 mm/h on basis of 8 measurements with the 1.5 x 1.5 meter infiltrometer in two locations at ICRISAT's research station (ICRISAT, 1977), which is of the same order as those found in the infiltration cylinders.

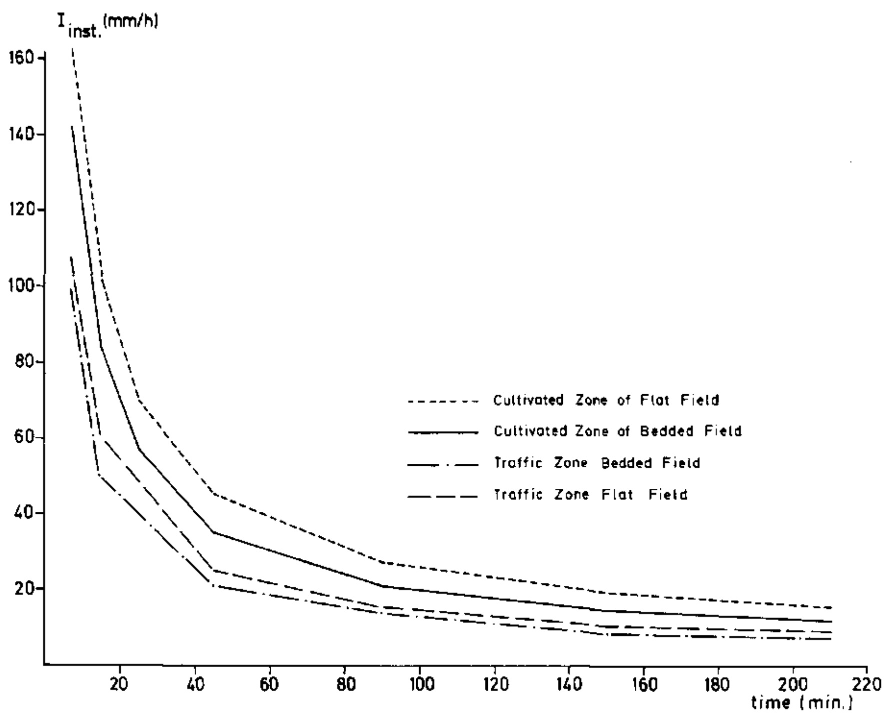


Figure 5.8. Infiltrability of cultivated zone and traffic zone of an Alfisol, after correction for lateral flow.

Total field infiltration, though strongly related to the infiltrability, also depends on other factors, as can be understood from figure 5.1. Surface storage of water, which is the combined effect of depression storage, surface retention and surface detention, increases the time available for infiltration while surface slaking reduces this storage capacity and induces crust formation upon drying which leaves the surface in a low permeable condition *(section 6.1.1.)*.

5.3.2. Evapotranspiration

Mean annual potential evapotranspiration (ET_o) for Hyderabad, India, is reported to be about 1,750 mm (Virmani *et.al.*, 1980b). As Dancette and Hillel (1979) illustrate for data obtained in a similar monsoon-climate at Bambey, Senegal, variation of potential evapotranspiration between years is small compared with the large variation of annual rainfall. For Hyderabad, highest mean daily rates are measured during the hot and dry summer season, with an average of 7 mm/day for the month of May *(Figure 5.4.)*, followed by a sharp drop upon the onset of the monsoon season. Winter-values are also relatively low. Single day values could be much higher (over 10 mm/day), while the values go down to as low as 3 mm for rainy days.
Maximum evapotranspiration (ET_m) is defined as the maximum actual evapotranspiration of an actively growing crop, if availability of water and crop cover are no restriction. Its value depends on micro-meteorological conditions, such as temperature, radiation, humidity and wind, and crop characteristics such as density and aerodynamic roughness of the crop. ET_m-values can be measured with the help of a number of different approaches. Tanner (1967) classified these into water-balance or hydrologic methods, micrometeorological methods and empirical methods.

Values of actual evapotranspiration (ET_a) are generally lower and mostly only a fraction of the potential rates. Transpiration can only take place if transpiring plants are present, evaporation depends on the availability of water at the evaporating surface. Shortly after rainfall, water intercepted by the crop canopy or mulch material and water stagnating in depressions is available for evaporation. Otherwise, all water contributing to the actual evapotranspiration originates from the soil profile.

Actual evapotranspiration during the growing season could approximate the maximum rates in a well-watered field with fully developed crop canopy. As the level of available soil moisture decreases, actual evapotranspiration will decline. The value of ET_a then not only depends on the level of available moisture, but also on the atmospheric demand and on the rate of profile water delivery (Holmes and Robertson, 1963). Shaw (1980) presented a diagram of this relative rate of ET as influenced by the available moisture and the type of demand *(Figure 5.9.)*. The figure is based on data obtained in an earlier experiment on maize plants grown in containers filled with a sandy clay loam (Denmead and Shaw, 1962). The observations relate to the period that the roots were still growing, so that a displacement of the curves towards the left can be anticipated towards the end of the growing season.

Part of the water retained will be lost through direct evaporation at the surface. The level of this evaporation initially approaches the evaporation from a free water surface, Later on, it is controlled by capillary transport which is a much slower process. Finally, it is gradually taken over by the extremely slow process of vapour transport through nearly dry soil.

Simple relationships for Alfisols to estimate the daily evaporative loss during short periods after rainfall were used by Singh and Russell (1979)

$$E^* = E_o/t \quad (t = 1, 2, 3, \ldots\ldots 10) \qquad (5.8.)$$

$$E = E^* \cdot \frac{R_{ns}}{R_{no}} \qquad (5.9.)$$

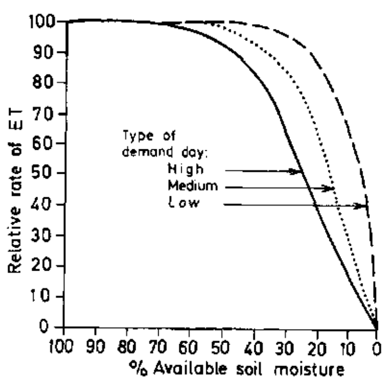


Figure 5.9. Relative transpiration rates for different levels of atmospheric demand. Derived from Shaw (1980).

with:

E^*	=	evaporation from a bare soil (mm/day);
E_o	=	open pan evaporation (mm/day);
t	=	number of days after recharging rain (-);
E	=	soil evaporation under a crop canopy (mm/day);
R_{ns}/R_{no}	=	fraction of net radiation energy received by the soil surface (-).

Equation 5.8. is valid for the evaporation starting from the end of rain, thus including the first stage of evaporation, when the surface is still wet and evaporation proceeds at an energy-limited rate (Jury, 1966). Relations given by several others (Black *et.al.* 1969; Ritchie, 1972; Tanner and Jury, 1976) are of the form:

$$E_{cum} = C\sqrt{t} \qquad (5.10.)$$

with:

E_{cum}	=	cumulative evaporation (mm);
C	=	parameter related to soil physical characteristics.

This form is meant to describe the evaporation in its "second stage" (Ritchie) or "falling rate" (Tanner and Jury) after the topsoil has dried. Black observed this relation in sandy soils for the complete range of drying.

Equation 5.8., when compared to Equation 5.10. suggests a higher evaporation during the first 6 days after wetting, but a lower rate later on. According to Russell, (personal communication), the high evaporative demand in the semi-arid tropics and the sandy nature of the Alfisols justify the use of Equation 5.8. This was experimentally confirmed by Vollebergh (1984) on the basis of evaporation measurements, using small buried tubes, at ICRISAT station. With these experiments he also observed the extremely short duration of the first stage drying for an Alfisol, always less than a day.

5.3.3. Crop-Available Profile Moisture

The soil profile is the medium of root growth giving mechanical support to the plant and acting as a reservoir for nutrients and moisture. Looking at the moisture aspects, there are a number of physical characteristics, based on texture, structure and depth of the profile, that determine the profile's usefulness and effectiveness as moisture reservoir under certain climatic and topographic conditions. The corner stones of this are the infiltration, the water storage and water-release.

Infiltrability of the profile is influenced by structure and texture, layering and surface stability and determines the rate of acceptance of water. Surface topography, including local slope and depression storage influences the time available for water to infiltrate *(section 5.4.)*.
The amount of water that remains in a profile some time after complete wetting is defined as field capacity, generally expressed as a layerwise volumetric percentage. Only part of this stored water is available for transpiration as the water, held at suctions above 15 bar (permanent wilting point) cannot be extracted by plant-roots. The rate of extraction by roots depends on the soil capillary conductivity which decreases rapidly as soil suction rises (Russell, 1973). Level of available water, therefore, also depends on the rooting pattern, rooting depth and transpiration rate and is therefore related to crop characteristics and actual climatic conditions. Moreover, moisture stored below the rooted profile can move upward in dry periods. A generalised water availability profile for medium deep and deep red soils would have the shape shown in figure 5.10.

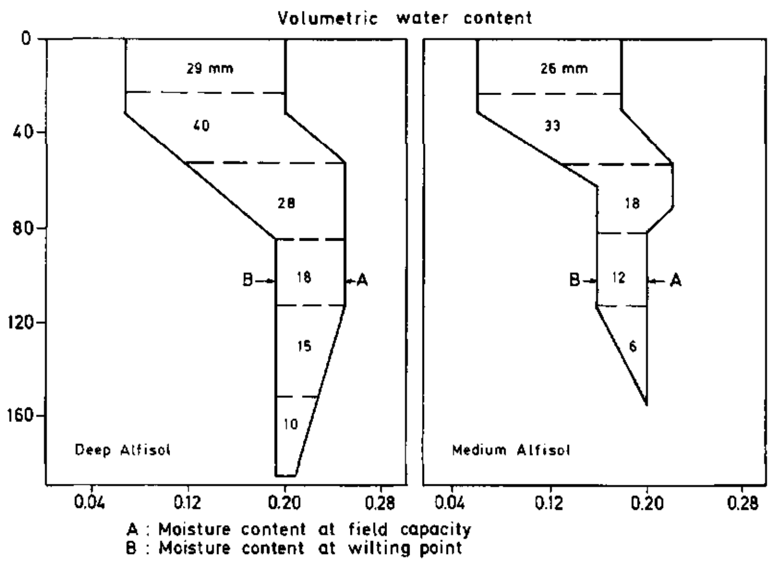


Figure 5.10. Available water profiles for a deep and medium deep Alfisol. ICRISAT (1978).

The total quantity of available moisture differs at each location; it ranges from as low as 50 mm for very shallow red soils to about 150 mm for the deep ones. The consequences of the level of profile storage are two-fold. Firstly, shallow soils show a much higher incidence of crop water stress, as they have a low buffer capacity. Secondly, length of the growing season is shorter mainly because of the absence of a reasonable amount of residual moisture at the end of the rainy season. For Hyderabad conditions, Virmani *et. al.* (1980 b) estimated the length of the growing season at 15 and 19 weeks for an available water storage capacity of 50 and 150 mm respectively, based on a 75% probability.

Water losses through evaporation are highest immediately after rainfall in a field lacking cover. Equation 5.8., section 5.3.2., implies that the cumulative evaporation between storms equals twice or thrice the daily potential evaporation for intervals of 4 and 11 days respectively. Additional dry days do not add much to the total evaporation. Rainfall pattern (frequency and storm-sizes), therefore, determines to a large extent the absolute quantity of direct evaporation.

Direct evaporation from the soil is the major water consumer before sowing (apart from transpiration by weeds) and at the early stage of crop growth a severe competitor for the emerging crop. At this stage both evaporative demand and transpiration by seedlings depend on water from the same layer of the profile. As the roots elongate and crop canopy develops the competition for water shows a different picture:
- water requirement for transpiration increases;
- evaporation losses are diminished under the protective cover of the crop canopy;
- the depth from which water is used becomes larger as the bulk of evaporative water-loss takes place from the upper 20-30 cm (Henderson, 1979) whereas roots tend to grow much deeper.

The competition for water is now indirect; the amount of water lost from the topsoil by evaporation has to be replenished by the next storm before deeper layers get additional inflow. Weeds are also active competitors at this stage and should be controlled.

5.4. Excess Rainfall and Depression Storage

Each time the intensity of rainfall exceeds the actual infiltrability at some point in the field, free water will start building up on that spot. If this spot is higher than its surroundings water will flow to an adjacent lower place, where it either infiltrates or adds to the excess water there. If a point is surrounded by areas of a higher elevation, the excess water will stagnate in this depression. The water level rises as long as rainfall and inflow from elsewhere exceed infiltration. This continues until the water rises high enough to overtop the rim of the depression; from this stage onward, additional water will flow out, either to fill neighbouring depressions or to add to surface runoff.

Mitchell and Jones (1978) as well as Moore and Larson (1979) identify three stages in the process of rainfall, depression storage and runoff:
- A build-up of depression storage without runoff;
- Additional storage, accompanied by runoff;
- Maximum depression storage, with all excess water contributing to runoff.

Linsley *et.al.* (1949) expect the duration of the first stage to be extremely short, but its actual length will depend on local conditions. Overland flow begins at the very moment that the infiltrability of the soil profile is exceeded. This process starts at one point and will subsequently include an increasing number of points, unless the rainfall intensity is barely higher than the infiltration rate. A field is covered with a large number of micro depressions, and most of the initial flowing water will reach such depressions before it can leave the area. Moreover, as the water originates from spots with the lowest local infiltration, or the highest local rainfall (spots oriented at wind direction), it may pass through other locations with more favourable infiltration conditions soon after it started flowing. Depression storage, therefore, may cause an appreciable time-lag in runoff, esp. if rainfall intensity is not much larger than the actual infiltration rate.

To understand the behaviour of depression storage, it should be realised that, as listed by Linsley *et.al.* (1949):
- Each depression has its own capacity or maximum depth;
- After each depression is filled to capacity, further inflow is balanced by outflow, infiltration and evaporation;
- Depressions of various sizes are both superimposed and interconnected. In other words, any large depression encompasses many interconnected smaller ones;
- Each depression, until completely filled, has its own drainage area.

As mentioned in section 5.1. three levels of depression storage can be distinguished in the field: micro-depression storage, mini-depression storage, and macro-depression storage. These levels differ in individual capacity, frequency of occurrence, stability and whether or not they can be created with tillage. These characteristics determine the effectiveness of the depression storage of a field for water conservation under a given rainfall regime.

5.4.1. Micro-depressions

Micro-relief depressions or micro-depressions are small. They can be of natural origin, but in agricultural fields they are mostly created by tillage. Between the structural elements formed free water can be trapped. Therefore micro-depressions are connected to the tillage process: they are easily destroyed or displaced as their dimensions are small compared to those of the tillage implements. They are easily destroyed by the process of slaking during rainfall.

Surface roughness is a measure related to the presence and size of such micro-depressions and related to the level of micro-depression storage or surface retention (Monteith, 1974). This effect on infiltration is difficult to measure, as the creation of roughness by tillage goes along with the breaking of the surface crust, both have a similar effect on infiltrability. Similary, the reduction of depression storage by slaking is accompanied by crust formation. After destruction of the surface aggregates by rain, smooth and shallow micro-depressions are left. Their capacity to retain water is low. Because of their shallowness, it is strongly related to the local slope of the surface. In flat cultivated fields this slope roughly equals the natural slope, but in bedded fields it is mainly fixed by the shape of the bed. Comparing these two situations, it is clear that this stable micro-depression storage capacity is far higher on flat cultivated fields than on bedded fields.

As indicated by Allmaras *et.al.* (1966) and by Burwell *et.al.* (1966) a differentiation should be made between oriented roughness, consisting of undulations in the surface relief related to the direction of tillage and random roughness, which is the random occurrence of surface peaks and depressions not oriented in any specific direction. In contrast to oriented roughness, random roughness produces closed depressions, responsible for the micro-depression storage of a field *(Appendix 5)*.

The potential water storage in surface mirco-depressions is constantly changed during a growing season by rain, wind and cultivation (Gayle and Skaggs, 1978). It basically depends on roughness, configuration and orientation of the small depressions with respect to slope direction. Monteith (1974) and Gayle and Skaggs have made direct measurements of surface storage by sealing the soil surface in small plots after cultivation and applying water until runoff has occurred.

Monteith envisaged correlation of level of depression storage to measured random roughness. Although he found a reasonable relationship between these factors in his experiments, he states that such regression may not be generally applicable, apparently also because he did not exclude the oriented roughness in his measurements. Moreover, in concurrent experiments by trying to correlate surface storage with runoff characteristics he found a very low relationship between them for soils that break down easiliy. His conclusions, therefore, remain in generalised terms, stating that the higher the roughness index, the higher the surface storage, the greater the time to initial runoff and the lower the total runoff in the first 30 minutes after commencement of rain.

Gayle and Skaggss intended to show the level of micro-storage for cultivated soils and its change during the year. Highest values, from 14 to 23 mm, were found for an organic soil immediately after primary tillage with a disk-plough. Weathering and secondary cultivation lowered this micro-storage to values below 1 mm, for different soil types at the end of the season *(Figure 5.11.)*.

Several researchers also tried to estimate a value for depression storage through mathematical methods *(Appendix 6)*.

A major decrease of random roughness or surface storage is reported to take place in the first 10 to 15 minutes of the rainstorm (Monteith), in the first few minutes of rainfall (Mitchell and Jones, 1978; Moore and Larson,

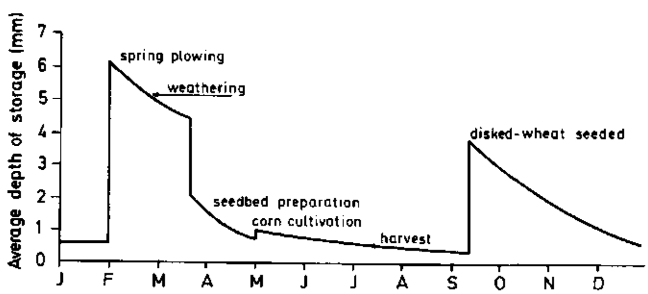


Figure 5.11. Example of the annual variation in micro-depression storage (surface retention) for a sandy loam soil.
Derived from Gayle and Skaggs (1978).

1979) or prior to initial runoff (Burwell *et.al.*, 1966). For Alfisols an early decrease was also observed for an unprotected surface, related to storm characteristics and the occurrence of runoff *(Appendix 10)*. Reduction of the depression storage might be stronger than that of roughness, as flowing water might open up outlets.

5.4.2. Mini-depressions

Mini-depressions are defined here as clearly visible topographic irregularities of the soil surface extending over distances around 10-50 cm. Most commonly, mini-depressions in agricultural fields are unintended marks of wheels, draft animals or implements. During field operations they might be removed or recreated. Such mini-depressions may contain an appreciable depth of water individually, but their low density of occurrence makes them relatively less important in the total depression storage capacity of a field.

Mini-depressions, however, could also be made intentionally and at a much higher density, through the creation of surface relief. In this case appreciable storage can be created. Such depressions do not exceed the distance between rows or plants in horizontal dimensions.

Well-known man-made mini-depressions are created through the technique of tied-ridging or basin listing, the English and American equivalent respectively (Russell, 1973), and also called furrow-damming (Clark and Jones, 1981). This system is useful in low rainfall areas, where dry spells are interrupted by storms with intensities that are usually higher than infiltration rates. In this system the field lay out is in ridges with the furrows or alternate furrows (Lyle and Dixon, 1977) dammed at regular intervals. Thus small basins are created in which excess water will stagnate. Although siltation of these basins will reduce their infiltrability, most of the ponded water will increase the amount of profile moisture, while a lesser part evaporates.

Crops are sometimes grown at the bottom of the furrow, in highly permeable soils, but as prolonged water stagnation would damage most plants, planting on the ridge is preferred. Moreover intercultivation of the crops becomes problematic where furrows are cropped, unless this is done by hand.

5.4.3. Macro-depressions

Natural macro-depressions are formed by undulations of the land surface and cannot be removed without special effort (Gayle and Skaggs, 1978). The distance over which such depressions exist, is less than the dimensions in agricultural fields. But within the field, macro-depressions could cover an appreciable area and cause ponding of water. The creation of a surface configuration, like furrowing, confines the stagnating water to the furrows, thus reducing the storage capacity. Under otherwise similar topographic conditions, furrowed fields have a distinctly lower macro-depression storage than flat fields.

Stagnating water in these macro-depressions could interfere with normal agricultural practices, partly physically, especially where some level of mechanised farming is used, partly physiologically, as water concentration in these spots and insufficient drainage interferes with normal plant growth.

CHAPTER 6 APPROACHES TO INFLUENCE THE WATER-BALANCE AND THEIR EFFECTS

6.1. Influencing the Profile Water-balance

The maximum crop available water stored in the rooted profile is usually defined as its moisture content between field capacity and permanent wilting point (Bolt *et.al.*, 1970) and is a function of a number of soil characteristics. Actual availability over time is fixed by the in- and outflow components, forming the profile water-balance or profile water budget.

The variation of stored water may be represented by an equation of the form

$$\Delta S = I - D - ET \qquad (6.1.)$$

with:

ΔS = change in profile moisture content (mm);
I = infiltration (mm);
D = drainage beyond reach of rooted profile (mm);
ET = evapotranspiration (mm);

if lateral flow of water in the rooted profile is disregarded.

Under the conditions of rainfed farming in the red soils of the semi-arid tropics, part of the precipitation runs off as infiltrability of these soils is often lower than rainfall intensities. To increase the quantity of moisture available for productive transpiration by a crop under these conditions, infiltration (I) should be maximized while avoidable losses within the ET-factor, *in casu* direct evaporation from the soil surface and transpiration by weeds, should be minimized. Deep drainage (D) is a loss factor in situations where this water is not recoverable. This was the case in the situation studied.

6.1.1. Infiltration Inducement

Susceptibility of the soil profile for water intake is determined by the presence and distribution of pores and cracks (Russell, 1973), the channels of flow. The presence of pores, the porosity, can be physically defined as the percentage volume of voids in a unit volume of soil. It is also the parameter determining the water holding capacity of the tilled layer, the so-called plough layer storage of water (Larson, 1964). Porosity is higher in a well-aggregated loose soil, while compaction reduces it.

The distribution of pores in medium and heavy textured soils depends on the soil structure, defined by Lal (1979) as the arrangement of primary particles into aggregates. The soil structure cannot be measured directly, but is important for water transport as it is a representation of the size, distribution and continuity of the individual pores.

The infiltration into a soil profile is influenced by the permeability of its least permeable layer. Such a layer could be of natural origin, as for example a clayey horizon in an otherwise sandy soil or induced as a plough layer. But in practice, especially during high rainfall events and under non-saturated profile conditions, infiltration is determined by the surface characteristics rather than by the hydraulic properties of the deeper layers (Edwards, 1982). A prominent restrictive layer for infiltration in the red soils can be formed through compaction of the top layer and sealing under influence of raindrop impact and wetting *(section 3.2.)*. Permeability of this layer is shown to be far less than the value below such a crust (Mc. Intyre, 1958 b). By avoiding its formation or breaking the crust if already formed, infiltrability of the profile can be increased.

Permeability of a soil profile is also increased by the presence of vegetation (Cannel and Weeks, 1979). Growing roots also penetrate less permeable layers and profile boundaries, forming continuous pores and leaving channels for water transport after dying. Edwards observed that in a permanent vegetation on a non-tilled soil, preservation of micro-channels in the profile, and also crop residues, reduced runoff to a mere 5% of the quantity occurring in a similar cultivated field, although the porosity decreased from 50% to 40% in the non-tilled treatment.

A well developed crop canopy also moderates the soil temperature, preventing total dissication of the topsoil, which would otherwise make it hydrophobic. This also favours biological activity in this layer, inducing the creation of micro-channels. A similar effect is attained through mulching (Lal, 1976).

Unless changed through the execution of specialised and costly deep cultivation, the texture of the profile and its separate layers may be considered as given. But the structure is liable to change within the growing season or over the years. The latter occurs throughout the rooted profile as a long term process based on biological activity - including rooting -, enrichment by organic matter and demineralization. Seasonal changes are due to field operations and atmospheric influences, including gravitational forces and raindrop impact. These changes are restricted to the tilled layer (through cultivation) or even to the upper few centimeters (through rainfall impact), increasing or decreasing the infiltrability respectively.

Techniques of primary tillage, secondary tillage and protection of the land surface with a crop or with mulches, and their influence on infiltrability are discussed in the following sections.

6.1.1.1. Primary Tillage and its Effect on Infiltration

Primary tillage can only be executed when the field is in a suitable moisture condition. From the point of draft availability it would be optimal to execute the primary tillage operation immediately after harvest. Against this stands the alternative labour occupation for post-harvest activities. But even so, the red soils would often be too dry and consequently too hard to work. As an alternative, primary tillage should be executed immediately following a soaking rainfall which can be expected to occur during the pre-monsoon period.

Increase of porosity of the tilled layer can be tremendous and the duration of this effect may last, be it at decreasing importance, throughout the growing season. As Henderson (1979) describes, an increase of porosity of 10% to 20 cm depth increases infiltration by up to 20 mm for a single storm, under the assumption that voids are completely filled with water once the rainfall rate exceeds the subsoil infiltration rate and that the porosity lasts throughout the storm. A measurable residual effect of a deep tillage operation in the subsequent year should not be expected (Vittal *et.al.*, 1983).

In an observation at ICRISAT, two systems of primary tillage of a permanent raised bed of 1.50 m width (measured as furrow-to-furrow distance) were compared on the effect of water conservation. All operations were executed with a bullock-drawn wheeled tool-carrier with attached implements as described in Appendix 7.

System 1
This system of primary tillage for permanent raised beds was initiated at ICRISAT and originally meant for the Vertisol areas (ICRISAT, 1981) *(figure 6.1.(a))*.

It is a strip-ploughing operation that consists of cutting and turning inwards of the sides of the existing bed with the help of a left and right hand mold-board plough, transporting the soil to the centre. If done immediately after harvest, this operation can be executed with bullock-drawn equipment even in these clayey soils. In one or two additional operations the bed is shaped again and ready for seeding.

This system has been transferred to Alfisols without major modifications. Although such strip tillage system could also benefit red soils areas from the viewpoint of flexibility of operations it might not be effective enough to create the best plant environment. To improve on this, these structurally inert soils seem to require a higher intensity of cultivation (Charreau, 1977).

System 2
An alternative system of primary tillage was developed by Klay (1983) and experimentally introduced for use in red soil areas. It is denoted as intensive tillage. It is also based on the permanency of the location of

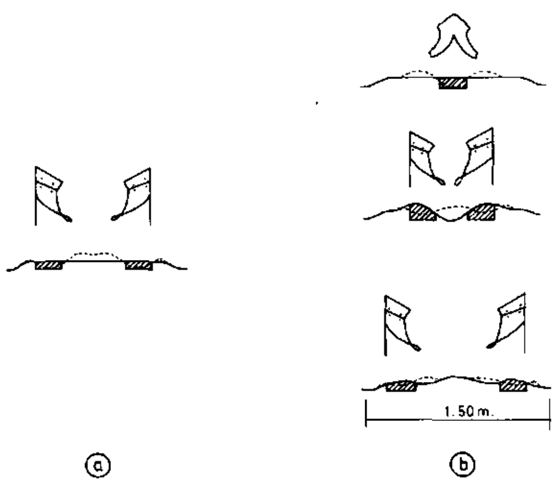


Figure 6.1. Primary tillage systems for red soils. (a) system 1: reduced tillage, (b) system 2: intensive tillage.
Derived from Klay (1983).

furrows and beds and includes the following steps of operation *(figure 6.1.(b))*:

- A ridger opens up the bed at the centre turning the soil both sides.
- Right and left hand ploughs spaced about 60 cm apart cut two strips on either side of the bed and transport the soil towards the centre, filling up the furrow created in the first operation.
- The same operation is repeated with the ploughs at about 90 cm apart.
- A spring-tyne cultivator and ridgers at 150 cm apart are used to finish the shape of the bed.

This system covers the full width of the bed.

A comparison was made between two adjacent plots of 4 beds with a length of 80 meters, that were tilled according to systems 1 and 2 respectively. Details on lay-out and observations are given in Appendix 8. During the period of observation a 20% reduction in runoff was measured for the intensively tilled beds of system 2. This reduction should be attributed to the higher porosity of the tilled layer, which makes the profile more receptive to water as well as to the better crop development in this plot.

The bulk density was measured on samples taken from the 2 - 7 cm depth. The intensive system of primary tillage yielded an extra porosity over the standard system of:

$$\frac{\rho a - \rho b}{\rho} \times 100\% = \frac{1.55 - 1.48}{2.65} \times 100\% = 2.7\% \qquad (6.2.)$$

With:

ρa = bulk density plot A (system 1) (g/cm^3).
ρb = bulk density plot B (system 2) (g/cm^3).
ρ = particle density (g/cm^3).

which, assuming the same difference over the top 15 cm, represents an additional water storage capacity of 15 x 0.027 = 0.4 cm = 4 mm.

It should be noted here, that the observations on bulk density were done towards the end of the rainy season and consequently represent the residual effect of the primary tillage executed some 2½ months earlier.

It should be realised, however, that the surface conditions may also be a limiting factor for infiltration. The usefulness of the extra porosity, therefore, is highest in situations where porosity would otherwise have been restrictive, i.e. either in situations of long duration, low intensity rainfall or at higher intensity rainfall when the surface crust is broken by recent cultivation.

Soil loss, measured as suspended material in the runoff water seemed to be highest from the intensively tilled plot, but insufficient data and the inaccurate method of sampling do not allow for definite conclusions.

As quality of plant stand has a definite effect on infiltration, primary tillage can also indirectly influence infiltration by enabling a faster development of the crop. This gives better protection against rainfall impact and is accompanied by deeper rooting. Willcocks (1981) reports this effect in two ways, one, showing an increase of sorghum yields with depth of primary tillage and secondly, between two systems of shallow tillage, through showing the superiority of a poly-disc tillage over sweep tillage. He ascribes the latter difference to the creation of a corrugated interface with the undisturbed soil of the profile. This causes lines of weakness through which roots penetrate more easily. These effects were observed for a ferruginous sandy loam soil. For a less dense and more sandy soil the deep loosening appeared unnecessary.

6.1.1.2. Secondary Tillage and its Effect on Infiltration

Secondary tillage could be defined as the cultivation practice executed after seeding of a crop, and is therefore synonymous with intercultivation. It is a shallowly executed operation as the residual effects of the earlier primary tillage do not require additional deep loosening. Moreover, to avoid mechanical damage to the emerging or standing crop, secondary tillage is bound to be restricted in depth and lateral soil transport.

In contrast to primary tillage, secondary tillage is repeated several times, generally up to the moment the density or height of the crop prohibits further entry into the field. This means that a decrease of its effects can be counteracted by a renewed cultivation, until the crop-canopy forms a more or less effective protection of the surface.

Shallow cultivation fulfills several objectives, such as:
- the control of weeds;
- incorporation of fertilizer;
- creation of a 'dust-mulch' to reduce evaporation;
- breaking of crust or compacted toplayer to promote infiltration;
- creation of surface roughness for micro-storage.

The last two objectives are aimed at improving the infiltration. The breaking-up of the top layer by shallow cultivation increases the infiltrability of the profile. It also creates micro-depression storage which allows more time for infiltration of excess rainfall. The effect on infiltration is the same for both mechanisms and is difficult to separate (Burwell and Larson, 1969).

The influence of tillage on the soil-physical conditions is a reversible one and subsequent rain destructs (part of) the created structure again, reducing its effectiveness and necessitating a repetition of the tillage operation.

There are more factors that determine whether or not a cultivation is appropriate. Crop stage has been mentioned already, but accessibility of the field and availability of time as competitive to other activities and costs involved should also be considered.

Additionally, the question could be asked as to how far more frequent tillage reduces the stability of the aggregates formed, inducing an easier decay of structure by raindrop impact. In this respect, Johnson *et.al.* (1979) stated that overtillage reduced the surface roughness. This question, however, relates to the natural stability of the aggregates. While mechanically applied forces tend to disrupt the natural stability, soils that are naturally unstable, like the red soils, can hardly be further disrupted by mechanical action.

Table 6.1. shows the influence of intercultivation on runoff and soil loss, measured for two series of ten runoff plots, each 45 m^2, in August - September 1980 *(Appendix 9)*. While no cultivation was done during this period in the series II plots, a shallow cultivation was executed in series I in the middle of the reported period. This cultivation proved to reduce runoff considerably at least for the subsequent two storms. With continuing rain, however, the runoff level increased again. The amount of soil transported by the runoff water was higher than for the plots left uncultivated. The rate at which this accelerated soil loss may occur after intercultivation, is unpredictable, as it depends, among other factors, on the size, sequence and intensity of storms. From the table it seems that in this specific situation, the benefits of increased infiltration through intercultivation have to be paid for by higher soil losses. However, this will not always be so, as periods between storms will generally be longer. Over the season one may expect a reduction of soil loss through cultivation, also because of a better crop development and earlier surface protection under the influence of water conservation.

Table 6.1. Runoff (mm) and soil loss (t/ha) from 45 m^2 plots. (RW-3F, 1980).
Plot series I : with shallow cultivation end of August (n = 6).
Plot series II : without intermediate cultivation (n = 5).

Date	P+)	WMI+)	Plot Series I Runoff	Plot Series I Soil Loss	Plot Series II Runoff	Plot Series II Soil Loss
	mm	mm/h	mm	t/ha	mm	t/ha
			same treatment			
30-7	23	24	6.1	0.42	5.7	0.27
6-8	22	24	7.2	0.40	6.7	0.30
13-8	13	21	1.5	0.10	1.7	0.06
14-8	13	30	3.7	0.22	3.3	0.14
20-8	56	25	5.8	0.38	10.6	0.53
Subtotal			24.3	1.52	28.0	1.30
			cultivation		no cultivation	
2-9	30	152	0	0	11.1	0.11
3-9	20	25	1.6	0.12	7.1	0.07
6-9	30	31	15.0	0.62	> 20	0.17
18-9	12	12	6.1	0.07	4.5	0.16
Subtotal			22.7	0.82	> 42	0.51

+) P = Precipitation
WMI = Weighed Mean Intensity of storm.

A more elaborate experiment was executed during the 1982 rainy season+). Objectives were to get a better insight into the influence of secondary tillage on runoff and the stability of the surface roughness induced. Details on lay-out and observations are described in Appendix 10. On the basis of runoff measurements for 7 storms, regression lines could be derived, indicating the runoff as influenced by cultivation, storm size and rain intensity. Figure 6.2. shows the runoff from cultivated plots as percentage of runoff from the uncultivated controls.

With this information and the distribution of rainstorm sizes over the year *(section 5.2.1.)* we can estimate the expected conservation of water through repeated cultivation of a fallow field. For a wide range of storm-sizes rainfall quantity and weighed mean intensity of the storm were not related *(section 5.2.2.)*. For this calculation therefore, we assume a W.M.I. of

+) The experimental work was carried out by Mr. S.J. Weststeyn as a thesis-subject. His participation is acknowledged.

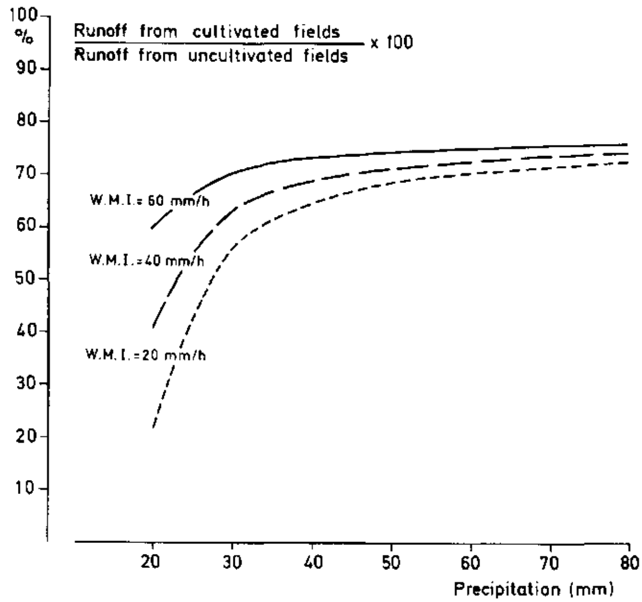


Figure 6.2. Runoff from cultivated fields as a percentage of runoff from uncultivated fields for different storm sizes and intensities.

40 mm/h for all storms, which is on the safe side. Small storms might have a lower intensity which would give a higher level of water conservation; for bigger storms, even if their intensity exceeded 40 mm/h, the behaviour would be similar for all intensities. The result of these calculations is shown in figure 6.3. as a 3-week moving average (histogram (a)) and as total conservation (line (b)).

Illustrative as they are, these figures can have no absolute value, as they relate to an unrealistic situation. The fields are unprotected against raindrop impact and have a higher moisture content than can be expected in a cropped situation. Both factors would otherwise lead to a higher infiltrability than used in the calculations leading to figure 6.3. The latter does show, however, the large influence of cultivation and the need to consider its frequency as well as surface protection.

Reliefmeter measurements during these experiments proved the instability of the tillage-induced roughness for this Alfisol. While a cultivation was seen to bring the Random Roughness Index (RRI), as defined in Appendix 5, to a value of 6 - 8 mm, a single runoff producing storm could reduce it again to 2 - 3 mm *(figure 6.4.)*. This reduction, partly related to the amount of rainfall, did not depend on the number of previous cultivations.

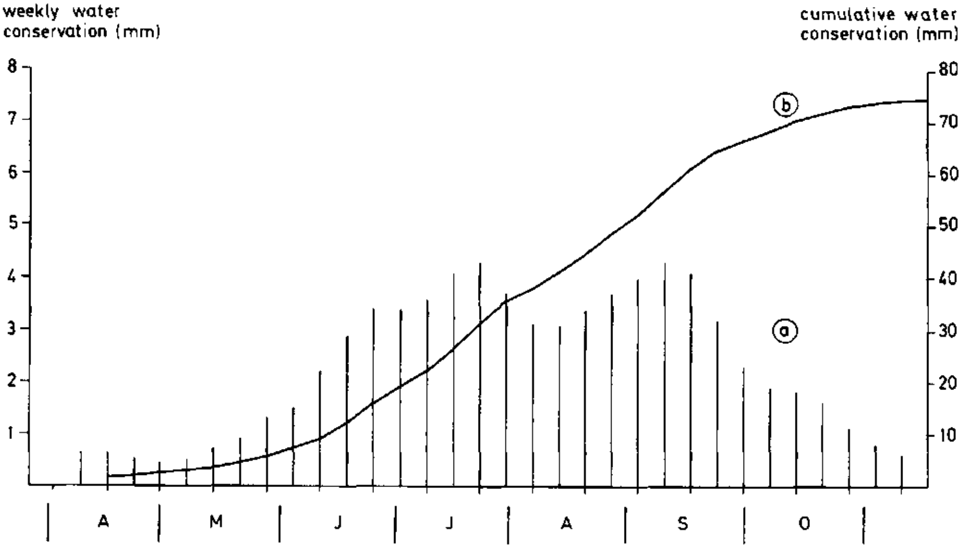


Figure 6.3. Theoretical water conservation through repeated superficial cultivation in a fallow Alfisol. (a) weekly values, (b) cumulative values.

In other words: the frequent cultivations did not reduce a form of natural stability *(Appendix 10)*. In practice, this means, as stated before, that repeated shallow cultivation has no appreciable effect on the stability of soil structure. To maximize water conservation, it should be repeated after a runoff producing rain, at least as long as no protection is given to the field through a crop canopy or a mulch.

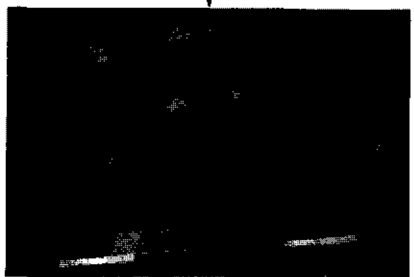
6.1.1.3. Maintaining Infiltrability through Crop Cover and Mulches

The role of a crop canopy in protecting the surface structure is related to its capacity to decrease the velocity and size of the raindrops during heavy storms. In this way, it reduces the kinetic energy that reaches the soil surface. Its effectiveness depends on the sizes, shape and density of the leaves. During the period of crop cover and -transpiration, the infiltrability of the profile will also remain higher because of biological activity and use of water.

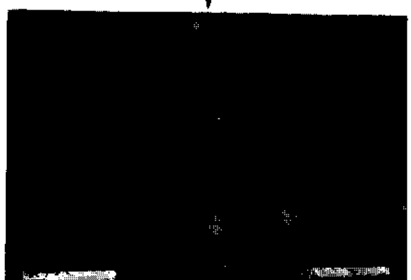
As a measure of crop cover the leaf area index (LAI) is usually taken. An alternative, used here, is the percentage of light interception which is measured at ICRISAT for different (inter) crops. Figure 6.5. gives a number

Date	Rainfall between RRI measurements (mm)
21/7	
	54 mm
27/7	
	62 mm
30/7	
	36 mm
13/8	

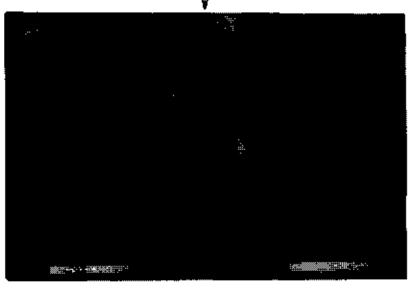
RRI = 7.8



RRI = 4.3

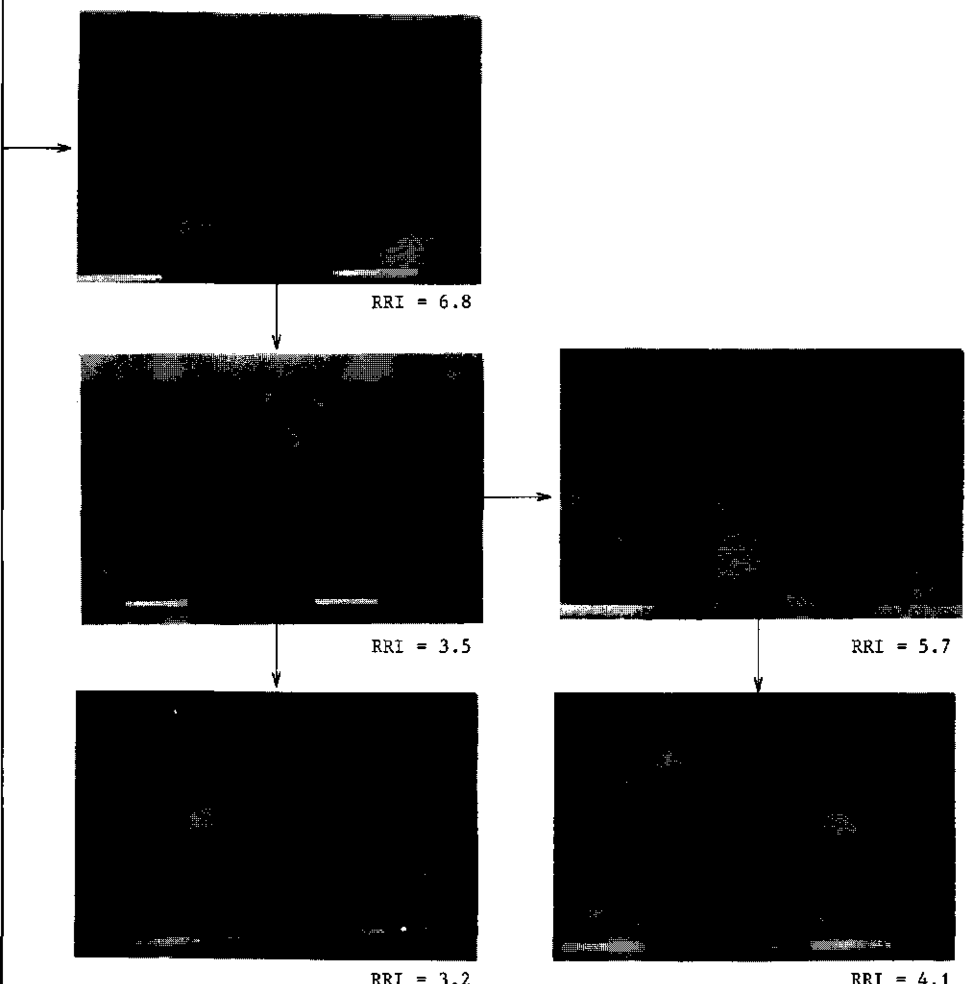


RRI = 2.9



RRI = 2.7

Figure 6.4. Random roughness index (RRI) of an Alfisol (RW-3C), as created by superficial cultivation (horizontal arrows) and subsequently decreased by rainfall (vertical arrows).



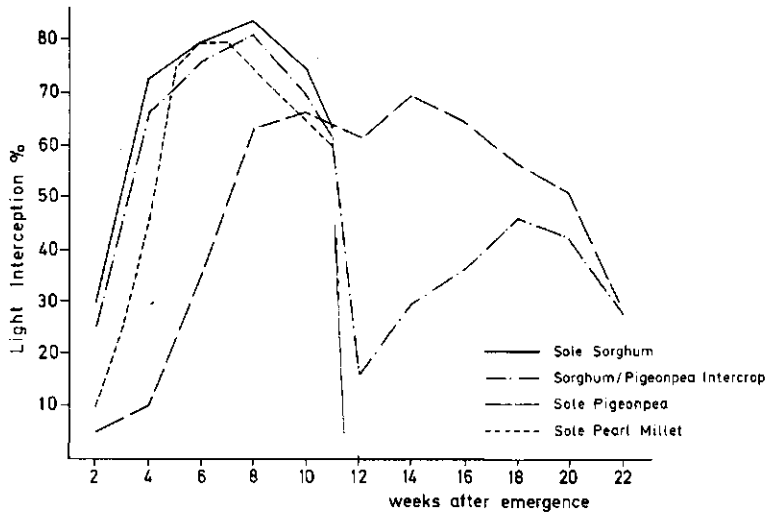


Figure 6.5. Light interception for some cropping systems at Hyderabad, India. Adapted from Natarajan and Willey (1981); Reddy and Willey (1981).

of such lines to show the periods and levels of protection one may expect from different crops or crop-combinations.

During periods of low cover, tillage is needed to maintain or increase infiltrability. The major benefits of secondary tillage for water conservation, can be expected between the first rains and full canopy development and again directly after removal of a component in an intercrop. These periods coincide with occasions on which secondary cultivation is possible and is also necessary for weed control.
Figure 6.5. also shows the differences in cover provided by various crops. Choice of crops (including crop combinations and varieties) and optimization of their growth environment are important in obtaining early cover.

Mulching, the application of (organic) material on the soil surface has been proven to give another effective protection, especially during the period of incomplete plant cover. Many authors have reported significant increase of infiltration through mulching (Mannering and Meyer, 1963; Unger, 1975; Lal, 1975). Apart from the direct effects on maintaining infiltrability through surface protection, mulching also reduces soil erosion, whereas repeated mulching and incorporation of the organic material will improve the topsoil structure, through an increase of biological activity (Vleeschauwer *et. al.* 1980). An increase of the profile retention capacity through frequent application of organic material, is shown to be insignificant (Russell, 1973). Although some of the reported data are impressive and worth bearing in mind, the reality of rainfed farming in semi-arid tropical regions generally does not allow for the use of organic material in the required quantities due to its alternative applications as fodder, construction material or fuel (FAO, 1977; Asseldonk and Stolwijk, 1983). *Jones and Wild (1975)* in this respect also mention the risk of a carry-over of insect-pests and the uneconomic nature of the operation.

Another method is the vertical placement of straw or other material in slots. This approach aims at a local inducement of infiltration. Clearly, required quantities of organic material are much less than in the case of surface mulching. Benefits of such use are reported by Rao *et.al.* (1977) for Southern India in an area of extremely low rainfall and heavy Vertisols with low infiltrability. The technique is costly, also in view of the fast decomposition of the material under tropical conditions. So far, it seems an acceptable water conservation method only if other approaches have no effect.

Live mulch or smother crops, apart from their own production potential, could have positive effects on infiltration, erosion reduction and weed suppression. Competition for available water in the profile, however, makes them less suitable for use on the red soils of the semi-arid tropics.

6.1.2. Reducing Evapotranspiration

Evaporation from the soil surface and transpiration of weeds are loss-factors in the profile waterbalance. The latter can be minimized by timely cultivation. Amounts of water lost through evaporation are high immediately after wetting of the soil surface, especially if this surface is unprotected. By stimulating a good canopy development evaporative losses over much of the rainy season will be decreased whereas a protection throughout the rainy season could be created through the application of sufficient mulch. However, apart from the problem of availability of sufficient mulching materials, mentioned before, large quantities of mulch hamper mechanical operations. Henderson (1979) also indicates that rain interception by partially decomposed mulch will be appreciable, where the water is largely evaporated later on.

Reduction of evaporation can also be achieved by shallow cultivation, creating a "soil-mulch" or "dust-mulch" (Féodoroff and Rafi, 1963). This disrupts the continuity of pores, changing the upward water movement by capillary flow, to the much slower process of vapour diffusion. It could be argued that cultivation induces evaporation as it brings moist soil to the surface, creates a higher surface roughness, increasing contact with the atmosphere, and reduces the surface albedo. Nevertheless Linden (1982) came to the conclusion that changes in hydraulic properties of the soil were of more importance. For unstable soils, like the red soils, such cultivation might be even more effective. According to Welling (1965), their dense packing results in higher rates of upward water movement, compared to more aggregated soils.

A cultivation will promote complete and fast dissication of a thin top layer. The low water retention capacity of the red soils leads to deeper wetting. Thus it becomes more likely that useful amounts of water can be conserved in this way.

6.1.3. The Effects of Surface Configuration on Soil Moisture and Plant Establishment

In traditional agricultural systems in semi-arid India, crops are grown in flat cultivated fields. Introduction of a different surface configuration like ridges or beds, influences the surface water movement. The effects of this on a field scale and their consequences will be discussed in section 6.2.

In a separate experiment, observations were made to detect the local influence of the surface configuration. Differences in moisture content of the top soil and observed crop growth are supposed to reflect a different runoff performance and a different internal drainage of the top soil. In four replications, therefore, flat plots were compared to bedded plots in respect to layerwise profile moisture content, root growth and development of foliage *(Appendix 11)*.

The season was extremely wet, especially during the second half of August, when no sampling could be done. Yet, no clear differences could be observed in soil moisture between the two land management treatments *(figure 6.6.)*. On most dates, however, observed values are close to or at field capacity for both treatments (Appendix 11). During the period of about two weeks in August that could not be sampled, drainage might have been inferior in the flat cultivated plots, resulting in waterlogging.

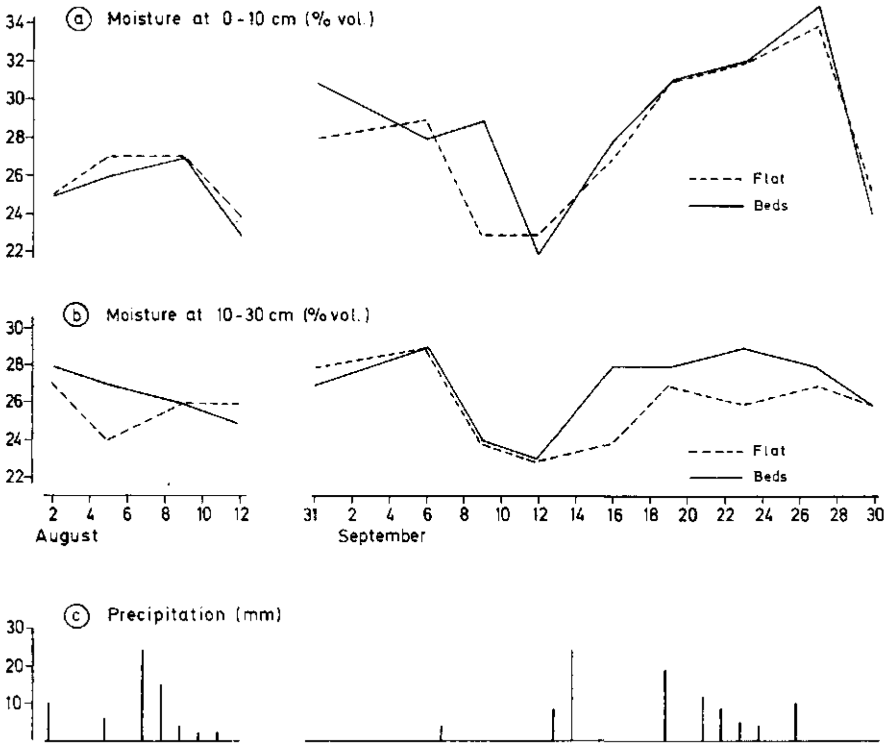


Figure 6.6. Profile moisture content under two surface configurations (RA-10, 1978).

In respect to crop growth at least, a much slower development was observed for the flat cultivated plots, as can be seen in figure 6.7. for root growth and table 6.2. for foliage development. The effect was temporary and was made up by subsequent growth.

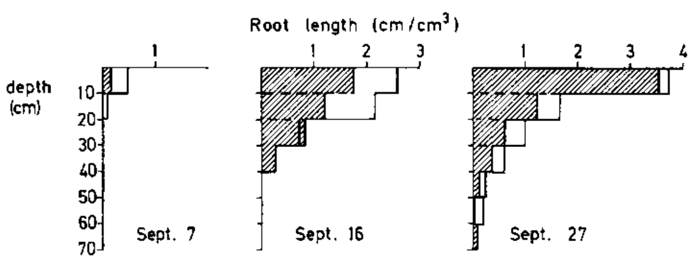


Figure 6.7. Comparison of root growth between flat (shaded) and bedded plots (RA-10, 1978).

Table 6.2. Leaf-area and corresponding dry matter weight of a 50 cm Pearl Millet row for two different surface configurations and three replications. (ICRISAT, RA-10, 1978)

	Leaf area (cm^2)				Dry matter weight (g)			
	1	2	3	Mean	1	2	3	Mean
Sept. 7								
Flat	250	260	150	220	1.6	1.7	0.9	1.4
Broadbeds	730	1200	525	818	4.2	6.8	2.9	4.6
Sept. 16								
Flat	1965	650	740	1118	12.7	5.1	4.9	7.6
Broadbeds	2087	2830	2265	2394	15.6	17.8	14.6	16.0
Sept. 27								
Flat	1815	1317	1298	1477	50.6	23.8	22.8	32.4
Broadbeds	1723	1588	1217	1509	34.9	43.2	26.6	34.9

6.1.4. Soil Moisture at the Start of the Cropping Season

Precipitation falling before the growing season can be stored in the profile. Losses occur through evaporation and possibly transpiration by weeds. A shorter interval between rains causes more storage through a reduction in evapotranspiration by increased cloudiness, lower temperatures and deeper infiltration. For Hyderabad, during the months of April and May, so called pre-monsoon showers can be expected, yielding an average of 50 mm of rain. Over half of this rain occurs in showers of less than 20 mm, which, as a consequence of the high evaporative demand during this period, do not contribute to the moisture reserve, unless several showers occur within a few days.

After moistening to a depth of at least 15-20 cm the topsoil has become sufficiently soft to allow a primary tillage operation. Normal tillage depth is 10-15 cm. Subsequently, the rough and open ploughed layer will loose most of its stored water by evaporation. After a few more showers, when the top 30 cm of the profile has become moist, farmers will start sowing most of their crops. At this moment about 50 mm is stored. If early rains are scarce and time proceeds, sowing is done at a lower degree of moistening.

On red soils, water loss through evaporation is restricted to the top 20 to 30 cm of the profile. In this respect figure 6.8. is illustrative.

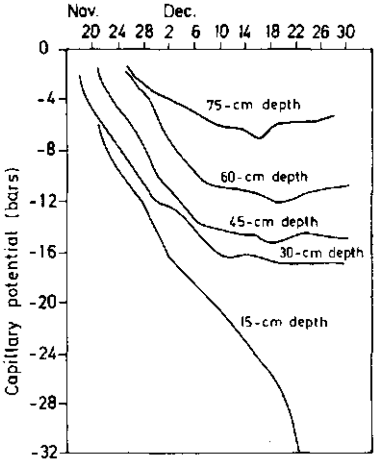


Figure 6.8. Capillary potentials under nonirrigated pearl millet on an Alfisol. Derived from ICRISAT (1978).

Moistening of deeper layers is not very probable during much of the pre-monsoon period, but may occur in certain years. In these cases it contributes to the moisture reserve available during the early part of the humid season.

6.2. Influencing the Field Water-Balance

Apart from increasing the infiltrability of the soil as discussed under 6.1.1., water conservation could also be promoted by keeping excess water on the soil surface. Total infiltration, therefore, is raised by increasing depression storage (Linsley, 1949) and by all measures that slow down the flow velocity of surface runoff.

Measures that influence the infiltration automatically have their effect on the field water-balance. Excess water, however, has to be drained to avoid waterlogging. The surface drainage pattern of a field is strongly influenced by topographical factors. These include the size, shape and slope of the field as well as the direction of furrows, or the presence of natural drainage ways. Topographic features determine the time of concentration of runoff from the field, which influences the level of peak flow at the outlet point. Higher peak flows require higher capacities of drainage channels and structures to prevent overtopping and erosion.

The creation of a surface configuration on a field can have a number of objectives including its influence on the movement of water. The choice of a bed-and-furrow configuration, for example, could be based on the following considerations:

- The bed, being the crop-management zone is created as a loose soil body and is not compacted by traffic, keeping infiltration and aeration optimal. Less hardening also allows for an easier cultivation. As this is a zonal tillage, energy and time are saved with most operations.
- The use of beds favours an early drainage of the topsoil after heavy rain through its higher topographical location, and specifically avoids stagnation of water in crop rows at locations in the field where macro-depressions occur.
- Using the furrows as guidance for draft animals and wheeled equipment, allows field operations to be executed fast and accurately in respect to lining and depth regulation.
- The presence of furrows makes the construction of mini-depression storage within the furrows and outside the crop rows possible.
- The construction of furrows makes it possible to influence the total travel distance for runoff water and its flow-velocity, by means of selecting the direction of the furrows (determining their slope) and their density, shape and size.
- The presence of the furrows enables efficient supplementary irrigation.

Consequences of a bed-and-furrow system, that should be considered as negative compared to the equivalent of flat cultivation, comprise:

- The decrease of effective micro-depression storage on beds as a consequence of their generally crowned shape.
- The concentration of runoff water in the most compacted, so least permeable, parts of the field, the furrows, accelerating the rate of runoff in non-cracking soils, particularly at small runoff events.
- The need for adjusted equipment.

6.2.1. The Effects of Depression Storage

The availability of depression storage capacity in a field can strongly affect the volume of runoff. At field-scale the three types of depression storage (micro-, mini- and macro-) *(section 4.1.)* could all be present. While the micro-depression storage is related to the surface roughness *(section 6.1.1.2.)*, the other forms are influenced by the surface configuration given to the field, or by other lay-out features.

The influence of the surface configuration on mini- and macro-depression storage is qualitatively shown in an experiment on an Alfisol at the ICRISAT-station *(Appendix 12)* where runoff from artificial rain was measured from 16 small plots with 4 different surface configurations, as schematically shown in figure 6.9.

The surface micro-structure was smooth for all plots due to earlier rainfall and not cultivated during the observation period. Runoff for three applications of rain at different dates and with different duration was measured.

The extreme variation in measured runoff between the replicates render the observed differences between treatments as not-significant. Still, as figure 6.10. shows, one can detect a tendency that, for small storms, the wave-type of surface configuration, which lacks storage capacity, has a higher runoff than the flat treatment characterised by the occurrence of depressions.

The surface configurations indicated as B and D are intermediate in this respect. At higher runoff events the differences disappear: depression storage causes a single subtraction of runoff per storm (or part of a storm), and does not influence the infiltration rate.

In contrast to micro-depressions, mini-depressions are more persistent and their effect on runoff may persist during most of the growing season. The capacity of such mini-depressions, expressed in mm of waterlayer is gener-

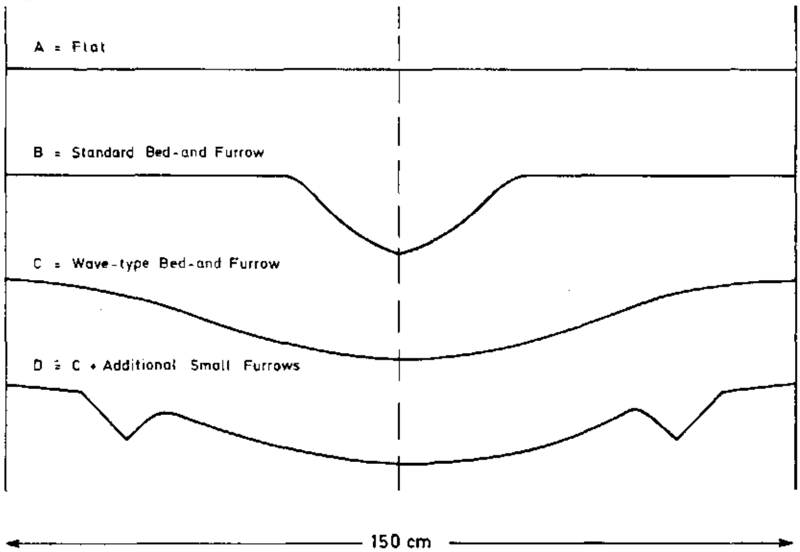


Figure 6.9. Schematic cross-sections of different surface configurations.

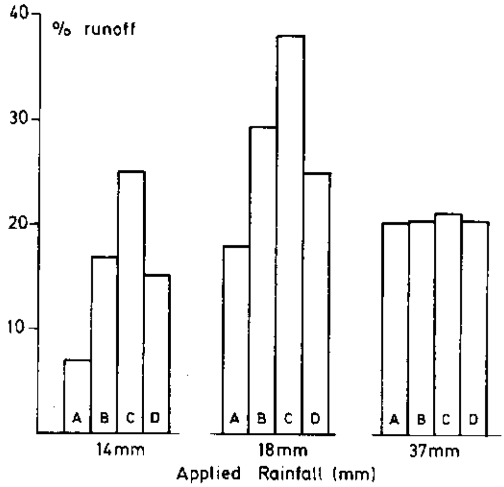


Figure 6.10. Percentage runoff from small plots with different surface configurations (A/D) and for different rainfall application (RW-ID, 1979).

ally low as they normally occur spotwise. Sometimes they are purposely created to retain excess water, as in tied-ridging *(section 5.2.2.)*, in which case the amount of water that can be conserved clearly depends on such factors as:

- cross-sectional size of furrow and ridge;
- height of dams;
- slope and interval of dams;
- soil characteristics;
- storm characteristics and frequency.

But the usefulness of tied-ridging in conserving water for increasing yield is not always clear, as this technique has its adverse effects on the required field-drainage. Clark and Jones (1981) for example report an excessively high level of storage, which made it possible to retain a rainstorm of up to 150 mm by damming the furrows at a 10% sloping area in Great Plains. Yield increase of dryland sorghum averaged 16% over 5 years. They do stress, however, the exclusive use of such systems during the growing period, when infiltrability and water use are relatively high due to the presence of a crop cover. In tied-ridging systems in fallow lands, lack of crop proved to be the reason for overtopping and washing out of the dams. Many other American experiences, however, show marginal or no advantage of tied-ridging (Lyle and Dixon, 1977). On the other hand, several positive results are reported from African experience. Starting with Faulkner (1944), who reported spectacular yield increases through tied-ridging for former Tanganyika, presently Tanzania, and Nigeria, also others (Peat and Brown, 1960; Dagg and Mc. Cartney, 1968; Lawes, 1961) report increases of yield by tied-ridging. The beneficial effects relate to seasons with below average rainfall; Adverse effects of standing water outweigh this advantage in wet years (Lawes, 1961).

Moreover, flowing water could over-top the small dams or the ridges themselves, leading to their destruction and a sudden release of water. To avoid this the storage capacity should be high enough to contain the maximum single storm expected. This makes the system unsuitable for many areas where expected runoff events are high or insufficient storage volume can be created, for example if contour furrowing cannot be accomplished accurately (Faulkner). A general awareness of this risk of over-topping and consequently uncontrolled flow seems to exist. Kowal (1970) adds other disadvantages to the indiscriminate use of tied-ridging, like problems of trafficability and waterlogging.

Earlier experiments at ICRISAT on tied-ridging did not show any positive effect on crop yield, indeed because too little storage volume could be created in view of the slope irregularities and instability of the soils.

6.2.2. The Effects of the Surface Configuration of the Field

Surface configuration has a direct effect on the level of mini- and macro-depression storage in a field *(section 6.2.1.)*. On top of this, differences in surface configuration may strongly influence the drainage of a field both in respect to aeration of the cropped zone as well as in respect to the flow pattern of excess water. Differences in surface configuration, therefore, may affect runoff and indirectly crop yield.

Runoff measurements from cropped fields, similar in shape and size (0.4 ha), but with different surface configurations, have been made for a number of years at ICRISAT-station. A summary of these observations is given in table 6.3., indicating the total seasonal runoff as percentage of the total precipitation during the same period.

The table shows that runoff from flat cultivated fields is generally lower than from bedded fields. Such difference would be in agreement with the tendency denoted in the earlier mentioned small plot observations

Table 6.3. Seasonal runoff as percentage of seasonal rainfall for two land management systems, 1979 - 1981 (ICRISAT, RW-3FH)

	Plot number[o)]					Average per treatment	
	1	2	3	4	5		
1979 (660 mm)							
Treatment[+)]	F	B	B	F	-	F	B
Runoff (%)	13.5	15.9	13.1	10.5	-	12.0	14.5
1980 (720 mm)							
Treatment	B	-	F	B	F	F	B
Runoff (%)	15.4	-	12.8	19.1	12.0	12.4	17.2
1981 (1095 mm)							
Treatment	B	F	B	-	F	F	B
Runoff (%)	28.3	20.5	19.5	-	15.5	18.0	23.9

+) F = Flat cultivated
B = Bed-and-furrow
o) Size of individual plots was about 0.4 hectare

(section 6.2.1.) inasfar as runoff would mainly originate from small runoff events. In that case, the higher level of stagnating water in flat cultivated fields would account for a high percentage runoff reduction.

Looking at the ratio's of runoff from flat plots and bedded plots for individual storms on Alfisols *(figure 6.11.)*, it can be seen that this ratio increases with increasing storm size. With small runoff producing storms, this ratio remains well below unity, indicating a higher runoff from the bedded plots.[+)] As storm size increases, runoff from flat and bedded fields tends to become more similar. The scatter in figure 6.11. is caused by the variations of factors like antecedent moisture, rainfall intensity and crop stage. Surprisingly, some of the deviating values, encircled in the figure, originate from runoff events that occurred shortly after cultivation and without appreciable crop cover. On these dates, the surface roughness is similar in both treatments and the related micro-depression storage is still dominant over differences in mini- and macro-depressions caused by land shaping. Therefore, differences between flat and bedded fields do not show clearly with such a rough surface.

Differences in runoff between plots with a different surface configuration and under natural rainfall were also monitored on smaller experimental

+) It should be noted that the opposite is true for Vertisols where runoff from flat fields is larger than from beds.

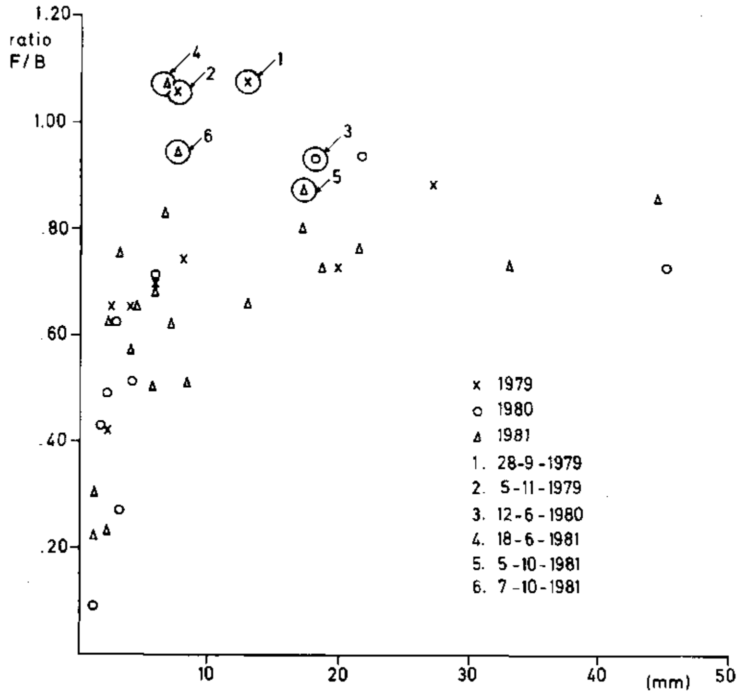


Figure 6.11. Ratio's of stormwise runoff from a flat cultivated field and a bedded field (F/B) as dependent on height of runoff. (Field sizes 0.4 ha).

plots *(Appendix 9)*. The comparison between the treatments A (flat cultivation) and B (beds with narrow furrows) was based on the mean values of two and five plots of 45 m^2 respectively. For five runoff producing storms the differences in runoff can be presented in relation to the storm characteristics as:

$$\text{runoff A/runoff B} = 0.82 + 0.02\ P - 0.01\ \text{W.M.I.} \qquad (R = 0.92) \qquad (6.3.)$$

with:

P = Precipitation (mm)

W.M.I. = Weighed Mean Intensity (mm/h)

Looking at the land shaping factors that influence the runoff, it can be seen that a difference in depression storage has a relatively stronger effect with small storms than with higher rainfall (see earlier).

Surface configuration, however, also influences the detention *(section 5.1.)*. Fields with straight and narrow flow channels will have less possibility of detaining water. With a higher wetted perimeter additional infiltration may occur and consequently less runoff. With low discharges flow channels are always small, so that differences between surface configurations in respect to detention are not apparent.

In the regression as given above, the co-efficients that go along with rainfall quantity (P) and intensity (W.M.I.), depend on the differences in depression storage and detention respectively of the compared configurations. The co-efficient for the rainfall quantity (+ 0.02) indicates the effect of a higher depression storage capacity of the flat cultivated plots. The co-efficient that goes along with the intensity (- 0.01) is an indication of the higher detention of the flat cultivated plots as compared to the bedded plot: at higher runoff rates the wetted perimeter increases most for the flat plots. Of course, equation 6.3. should not be extrapolated beyond the values from which it was derived, as the left hand ratio should tend to one at infinite P.

Crop Yield

The field scale plots were also monitored for their rainy season crop yield *(table 6.4.)*. After excluding the variability between years and plots, the yield of the flat cultivated plots seemed to be slightly higher than from the bedded fields. This difference, however, was far from significant.+) At first sight, this might seem strange in a situation where shortage of water is considered as one of the major limitations. Higher runoff would, as one would feel, result in distinctly lower yields. It should be realised, however, that in a relatively dry year, the difference in runoff is also low, and could hardly create a yield difference. In wetter years, the difference in runoff may become appreciable, but water availability might not be a major problem for any system. Moreover, differences in availabe water will influence crop yield, particularly if occurring during a dry spell. In our case, however, such differences are spread all over the season and obviously have little effect.

6.2.3. Hydraulic Properties of Different Furrow Shapes

Reporting the data on the influence of furrows on the outflow of an agri-

+) Production costs, however, were highest in the flat cultivated fields. For reason of comparison, improved implements were used for both treatments, wherever possible. For the flat cultivated fields, however, most operations required more time for execution.

Table 6.4. Yield of rainy season crop for two land management systems in field scale experiments (RW-3FH)

	Plot number				
	1	2	3	4	5
1978 (Sorghum)					
Treatment+)	F	B	B	F	B
Yield (t/ha)	3.49	2.33	3.80	2.93	1.77
1979 (Sorghum)					
Treatment	F	B	B	F	
Yield (t/ha)	3.12	2.40	2.52	2.76	
1980 (Pearl Millet)					
Treatment	B		F	B	F
Yield (t/ha)	2.03		1.42	1.78	1.43
1981 (Sorghum)					
Treatment	B	F	B		F
Yield (t/ha)	2.63	1.96	1.25		2.02

+) F = Flat cultivated
B = Bed-and-furrow

cultural field, no further specifications were given on the characteristics of the furrows themselves. Observations were made in fields where a "standard" lay-out of bed-and-furrow was used, and this was compared to the system of flat cultivation. The shape and the size of the furrow, however, has an important influence on its hydraulic properties and consequently on the field runoff. An experiment was done to quantify this hydraulic behaviour of two furrow types *(figure 6.12.)*.

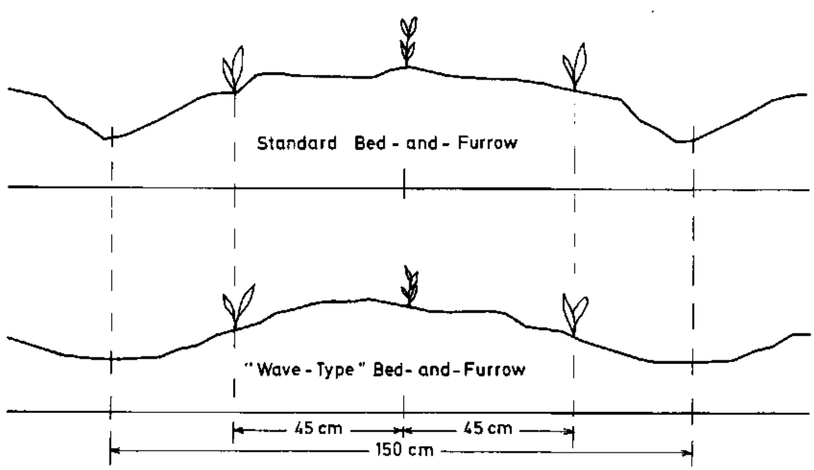


Figure 6.12. Cross-sections of two different shapes of beds, measured 6 weeks after sowing of a sorghum-pigeonpea intercrop.

For this, a known discharge of water was released at the upper end of 50 meter long furrows and outflow was measured as well as the wet cross-sections at intervals of 10 meter *(Appendix 13)*.

Outflow figures from wide furrows were distinctly lower than from narrow furrows with the same inflow. This can be explained by the difference in losses: the wet perimeter of the wide furrows is larger *(figure 6.13.)*. The higher wet cross section of the wide furrow also causes a lower flow velocity.

From these measurements an estimate can also be made of the hydraulic roughness of the furrow. Assuming Manning's flow equation is applicable:

$$Q = K \cdot A \cdot R^{2/3} \cdot S^{1/2} \qquad (6.4.)$$

with:

Q = discharge ($m^3 \cdot sec^{-1}$)
A = wet cross sectional area (m^2)
R = hydraulic radius (m)
S = slope (-)
K = roughness co-efficient ($m^{1/3} \cdot sec^{-1}$)

the calculated value of the roughness co-efficient K equals about 14 for the narrow furrows and might be a bit lower for lower flow rates. For wider furrows, with a water depth of only a few centimeters, K-values are around 7, and still lower at lower discharges.

The conditions in which the measurements were made differ from those during rainfall runoff; in the latter case the water losses from the wet furrows will be negligible, whereas in our experiment they were often 50% or more.

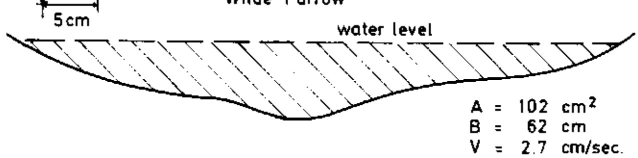


Figure 6.13. Characteristics of two types of furrows during flow of 17 l/min. (A = wet cross-section, P = wetted perimeter, V = flow velocity).

Moreover, along the furrow the volume of water increases during rainfall runoff, which is opposite to the flow conditions in the experiment.

An important difference is the concurrent influence of the depression storage on top of the beds during rainfall. Comparing beds-and-furrows which do not differ in furrow-to-furrow distance, beds with a wider furrow are less wide themselves and tend to have a more crowned shape. This, of course, will reduce the surface storage capacity on the bed. This gives an effect opposite to the effects of the furrow shape. The difference in furrow behaviour, therefore, is not clearly observed during natural runoff situations. Comparing mean outflow from 5 narrow with 8 wide furrows with slopes ranging from 0.3 to 0.5% and for 8 runoff producing storms, the outflow differed less than 10% *(Appendix 13)*. But, although this is true for the total runoff, on the basis of individual storms and related to their size and intensity, differences between the two shapes of bed-and-furrow appear again, as depicted in figure 6.14.

It can be concluded therefore that the overall effect of the shape of the furrow on runoff depends on the rainfall-runoff characteristics of the area in a particular season. With small size storms, the influence of depression storage reduces runoff; this gives better conservation in the combination of narrow furrows and a wide bed. The furrow characteristics show their influence during higher and more intense rainfall and conservation is better with wide furrows. Under the conditions of Hyderabad and as a

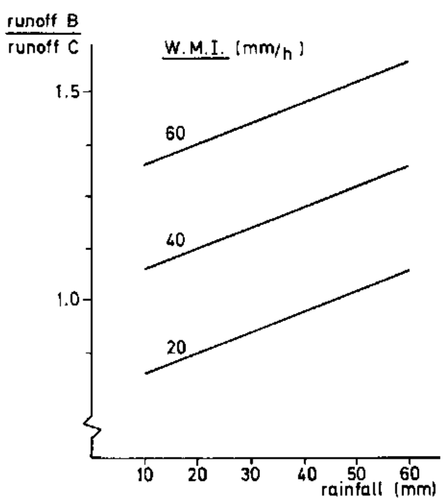


Figure 6.14. Ratio of observed runoff from narrow vs wide furrows (B/C) related to rainfall quantity (P) and intensity (W.M.I.) for 50 meter long furrows (RW-1C),1979, described as: B/C = 0.72 + 0.004 P + 0.010 W.M.I. (R = 0.92).

season's average, these two opposite effects tend to balance. But, realising the unequal distribution of heavy rainfall over the season, with a concentration later in the season, the crop would probably benefit more from a runoff reduction early in the season when the storms are smaller. This would favour the use of a type of bed-and-furrow with a maximum bed width. The bed should be shaped as level as possible to increase depression storage. The furrows should be made narrow in that case. A minimum size, however, is required to deal with the expected runoff and to avoid excessive flow velocities that would cause erosion. The measured K - Manning values could be used to estimate the minimum furrow-size required, and the longest permissible furrow length.

6.2.4. The Effects of Size and Shape of the Field

Within the field, a restriction of length of single furrows is advisable to avoid erosion in the lower stretch. Practical experience has shown that, at a mean slope of 0.4% in the direction of furrow, a length of 75 meters should be considered as the maximum advisable for standard beds. Flow velocities at the lower stretch of such a furrow can be estimated at 0.1 m/s at a high runoff intensity of 40 mm/h from 1.50 m wide beds. Field drains and outlet should be designed following criteria related to the expected height of peak flow.

Understandably, field size is an important parameter, but also its shape, as both determine the time of concentration (T_c) of runoff. T_c can be estimated from the empirical formula given by Kirpich (1940, cited by Raadsma and Schulze, 1974)

$$T_c = 0.0195 \cdot \left(\frac{L}{\sqrt{H/L}}\right)^{0.770} \qquad (6.5.)$$

with:

L = maximum length of travel (m)

H = difference in elevation between most remote point and outlet (m)

For a 0.5 ha field, with a natural slope of 2%, the time of concentration would range from about 5 to 8 minutes *(figure 6.15.)*.
For the range presumed in figure 6.15, the variation in T_c, from 5 to 8 minutes, corresponds with a ratio in expected maximum rainfall intensities of 1.33 (Jones *et.al.*, 1981). This ratio, if inserted in a runoff equation like the rational formula (Dickinson, 1980)

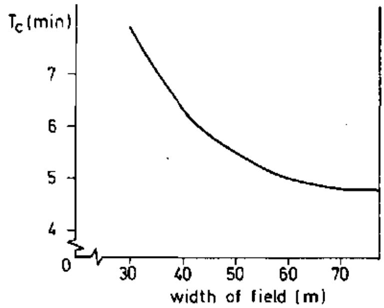


Figure 6.15. Time of concentration (T_c) as related to the width of a rectangular 0.5 ha field.

$$Q_p = 0.0027 \times C \times I \times A \qquad (6.6.)$$

with:

Q_p = Peak Runoff Rate (m^3/sec)

C = Runoff Co-efficient

I = Mean Rainfall Intensity over a period equal to Time of Concentration (mm/h)

A = Area (ha)

results in the same ratio in peak flow.

6.3. Influencing the Watershed Water-Balance

Under otherwise similar conditions, the surface outflow of a watershed, expressed as m^3/ha decreases with the increase in area covered (Shanan and Tadmor, 1979). Surface runoff water is held back in depressions or infiltrates, particularly if passing through watershed parts that are receiving less intense rainfall at that time.

The peak flow in m^3/s per hectare will decrease with increasing area as well as with a more elongated shape of the watershed. This can be understood from the reduced probability of receiving a high intensive rainstorm, covering all the contributing area, and from the increased time of concentration (T_c) for larger or more elongated areas. In small watersheds the second factor is the most important.

In many natural watersheds appreciable quantities of surface runoff water are stored in extended shallow depressions from where it partly infiltrates and partly evaporates. Some of such depressions could retain water for long periods of time. The waterbalance of a catchment could also be influenced by man-made constructions. Total surface runoff is increased by improving the surface drainage, or decreased by increasing infiltrability (by cultural measures), increasing the length of flow of the water (through diversions) or through the creation of storage capacity. The latter can be achieved by different means, like:

- Damming "oriented" depressions (furrows, valley's).
- Construction of excavated reservoirs.
- Construction of (contour) bunds.

Local topographic and agronomic conditions, possibilities of subsequent use of stored water and involved costs determine which is the most suitable alternative, if the major aim is reduction of outflow.

A useful distinction between the different techniques to create storage capacity could be made on the basis of their location within the watershed:
- near the crop (tied-ridging);
- in the lower part of individual fields (bunds);
- outside the field or group of fields, (excavated reservoir);
- at the lower reaches of the watershed (dammed natural depressions or valley's, "tanks").

The place where the water is stored, also influences its availability for irrigation, the location of the benefiting area and the level of control. Moreover, involved costs of construction and maintenance as well as safety of the system are distinctly different. In qualitative terms, important factors that characterize these differences are summarized in table 6.5.

6.3.1. Contour-Bunding

Since the inception of research on rainfed farming in India, measures have been proposed to decrease the amount of surface outflow of water and soil from agricultural fields. In this respect, most attention has been given to contour-bunds *(section 4.3.)*. Through these bunds, most of the surface runoff water and eroded soil particles are kept in the upstream area, reducing runoff on a watershed scale and simultaneously conserving water in the zones of submergence and seepage *(figure 6.16.(a))*.
Design criteria have changed over time, incorporating field experience, and depend on soil type and rainfall pattern (Rao, 1962).

Table 6.5. Characteristics of 4 levels of waterstorage systems for Alfisol-areas

	(1)	(2)	(3)	(4)
Location	Near crop	In field	Outside field	Outside agricultural watershed
Example	Tied ridging	Bunds	Small reservoirs	Large reservoirs ("Tanks")
Required land area	none	5 - 10%	10%	
Benefitting area	All field	Part of field	(Part of) area within watershed	Downstream of watershed
Benefitting crops	Standing crop	Standing crop	Standing and/ or subsequent crop	Subsequent crop
Benefitting period	Drought period following stagnation	- do -	Any subsequent drought and/ or subsequent crop	Following filling of reservoir
Reduction watershed outflow	moderate/high	high	moderate/high	none
Complications in field	waterlogging overtopping	waterlogging	-	-
Major water-losses	Some percolation	Moderate to high percolation	High percolation; high evaporation	Percolation; high evaporation
Water control	none	mostly none	good	good
Capital costs	none	low	very high	high
Variable costs	moderate	low	low-moderate	low
Risk of failure	very high	high	low	moderate

Since independence, 21 million hectares of agricultural land has been "bunded" in India at a cost of about Rs 250/- per hectare, constituting 90% of the total expenditure on soil conservation of agricultural land (Bali, 1980). But the lay-out of a watershed area based on contourbunds has not always been successful. In the first place, many farmers object to the loss of productive land, the division of their fields and to the curved lines of the bunds, which are very often a consequence of proper lay-outs (Bali, 1980). As a result, it is often not feasible for the executing agency to follow the recommendations required for an optimal lay-out. Secondly, prolonged water stagnation near the bunds could damage the crop and prohibit timely cultural operations (Gupta, *et.al.*, 1971) while the bunds are a

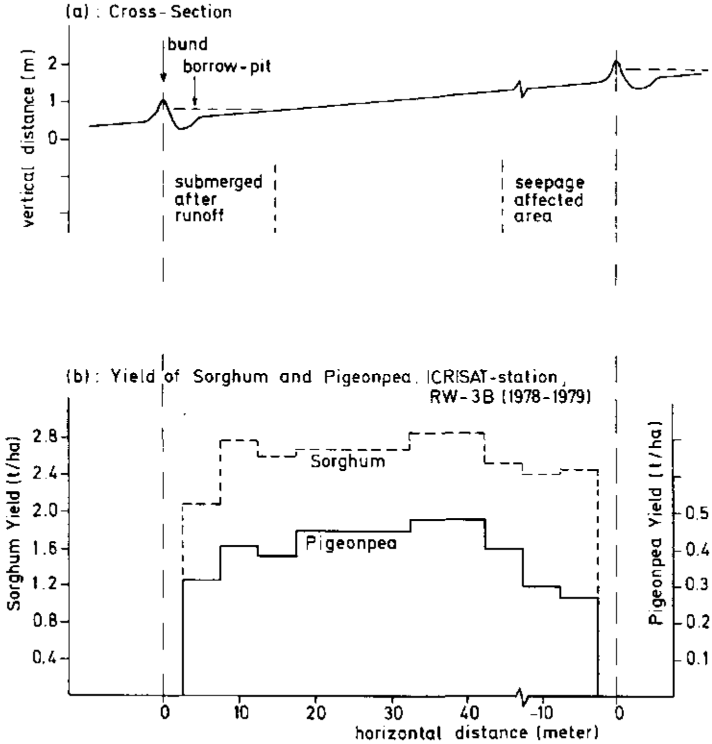


Figure 6.16. Longitudinal section of a contour-bunded field and of its yield.

source of weed infestation, resulting in disapproval by the cultivators. This adds to the already existing maintenance problems.

Although contourbunds could be suitable for reducing peak flow, improper construction and poor maintenance might lead to local breaching, through which high volumes of water are suddenly released. This causes more damage to the fields than would have been the case without bunds (Nanjundappa, 1981). Breaches do occur most easily in Vertisol areas, where the swelling and shrinking of the montmorrillonite clay make bunds unstable+).

+) Construction of contourbunds, therefore, is no longer advocated for these areas. Instead "graded bunds", which are constructed at a direction slightly deviating from the contour, are advised, together with the construction of grassed waterways. Such bunds hold less water during runoff producing rains, as they start draining immediately and dry out soon after cessation of rain. Their main function is runoff retardation.

For red soil areas, contourbunding programmes are still in progress. Besides the reduction of peak flow and total runoff, contourbunding is thought to increase crop yield at field level through the conservation of water. Several statements in this direction have been made over the years (Kanitkar, 1968; Bali, 1980). But although the concentration of additional water in a strip above the bund will saturate the profile, its moisture retention capacity as such is too low to bridge extended dry periods. Advantage through water conservation is therefore bound to be small. On the contrary, the stagnation of runoff water near the bund induces a sedimentation of suspended material, which decreases the infiltrability of the submerged strip, hence promoting waterlogging and suffocation of the crop.

Measurements during the rainy season in an Alfisol area at the experimental station of ICRISAT *(Appendix 14)* showed a decrease of infiltration from 6.2 mm/h immediately after the season's first ponding to about 2 mm/h during later events of water stagnation. Sedimentation and restricted water movement underneath the bund are both responsible for this reduction. As contourbunds are designed to hold water up to a height of 30 cm, it is clear that prolonged periods of standing water could occur. Submergence of most crops reduces their growth and yield due to aeration problems (Viets, 1967; Russel, 1973).

To document the influence of contourbunds on the crop on Alfisols, yield measurements were taken over a number of years, taking yield samples at varying distances from bunds *(Appendix 15)*. As an example figure 6.16.(b) gives the effect for both sorghum and pigeonpea, grown as an intercrop, during the 1978-1979 season at ICRISAT's experimental station. Yields were distinctly lower near the bunds and this reduction of yield was not only restricted to the upstream area of water stagnation, but also included the seepage zone downstream of the bund. Generally, a strip of about 5 meters in width including the bund and its borrowpit has virtually no production, due to lack of topsoil (used for bund construction), management problems, severe water stagnation and heavy weed infestation *(figure 6.17)*. In this particular year, characterised by frequent and heavy runoff, the average yield of the entire field, compared to the yield of the unaffected parts showed a reduction of 11% for sorghum and 17% for pigeonpea.

Contourbunds do reduce the quantity of sediment that leaves the fields. Additionally, bunds at regular intervals prevent excessive concentration of flowing water, which otherwise could have created gullies. Erosion within the field, as defined in Chapter 7, however, is hardly reduced, but leads to transport from the higher places towards the bund.

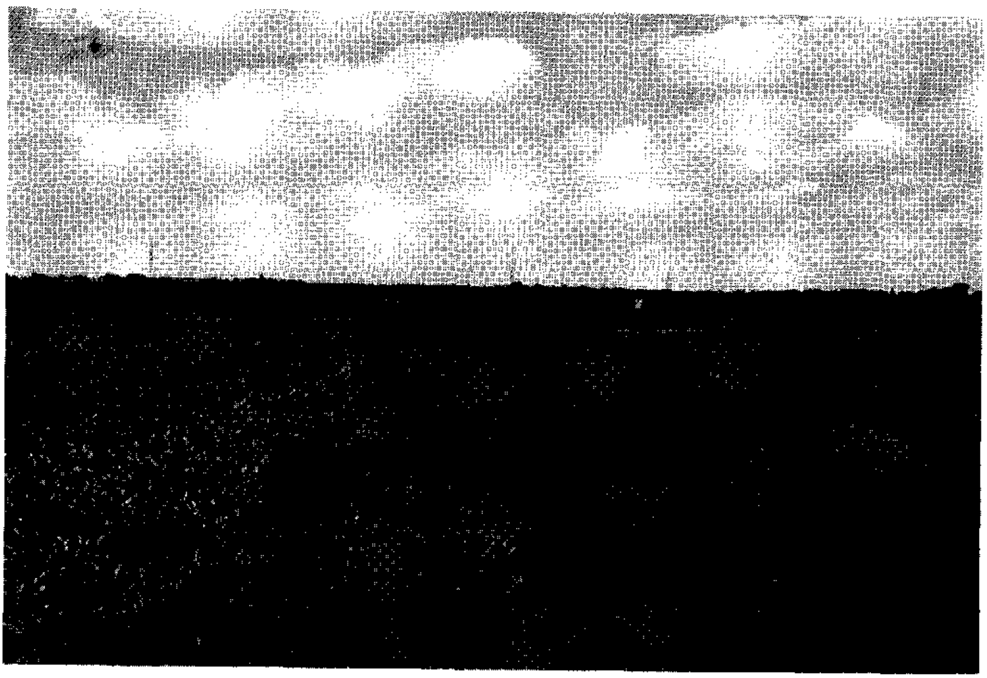


Figure 6.17. Poor plant stand near newly constructed contour-bund.

CHAPTER 7 EROSION AND SOIL LOSS OF RED SOILS

7.1. Definition and Description

Soil erosion is defined as the superficial removal of soil particles or the removal of a soil-mass under influence of water, wind and gravity. Most authors differentiate between geological erosion, as part of the process of soil formation, -transport and -sedimentation, and accelerated erosion, when this process is influenced by man, and results in an increased erosion rate. In agriculture, soil erosion comprises a loss of productive soil. In some situations the visible consequences could be very impressive. This includes the removal of soil from a field or area (formation of gullies), the transport of detached material (mud-streams, dust-bowl) or its deposition (siltation of reservoirs). These visible aspects of soil erosion, -transport and -sedimentation, often seem to overshadow qualitative factors.

Topsoil, the most valuable section of the profile is, as a consequence of its exposition, most vulnerable to erosive forces. Within this toplayer the soil particles are loosened and transported over short distances by raindrop splash, whereas the loose particles are susceptible to being washed out by the flowing water, as was observed by Ellison (1945). During the transport phase a further sorting takes place, as, the coarser the material, the earlier it will be deposited with a decrease of velocity of the transporting agent (wind or water). This selective process also implies a more than proportional removal of humus and nutrients from a field.

While erosion itself is a phenomenon that occurs within a defined area, be it a watershed, a field or a crop-row, soil loss, as a result of erosion, could be defined as the outflow of soil material from a certain area. Wischmeier (1976) in this respect uses the term sediment yield for a field or watershed as the sum of soil losses on slope segments minus occurring depositions. If one uses the amount of soil loss as a measure of severity of soil erosion in the contributing area, one should also try to include the amount of local sedimentation especially in non-productive areas like waterways.

A special case is the erosion and transport of soil material from a raised bed into the adjacent furrow, as far as it does not leave this furrow by subsequent transport. Reshaping of the bed-and-furrow as a normal cultivation practice returns all or part of this material to its original location, so that this amount should not be denoted as soil loss.

Red soils are highly susceptible to water-erosion. Because of their low aggregate stability *(section 3.2.)* they are easily dispersed into elementary soil particles: the concurrent surface sealing induces surface runoff and consequently transport of material. Following Baur's definitions (Baur, 1952), the most common form of erosion in flat cultivated fields is sheet erosion, described as "the removal of a fairly uniform layer of soil or material from the land surface by the action of rainfall and runoff" *(Figure 7.1.)*.

A transition to rill erosion, defined as "the removal of soil by running water with formation of shallow channels that can be smoothened out completely by cultivation", occurs if slopes are getting longer or steeper. It could be observed, therefore, in the lower part of flat cultivated fields, but also incidentally at the shoulders of raised beds, anywhere in the field, if a concentrated flow of water takes place.

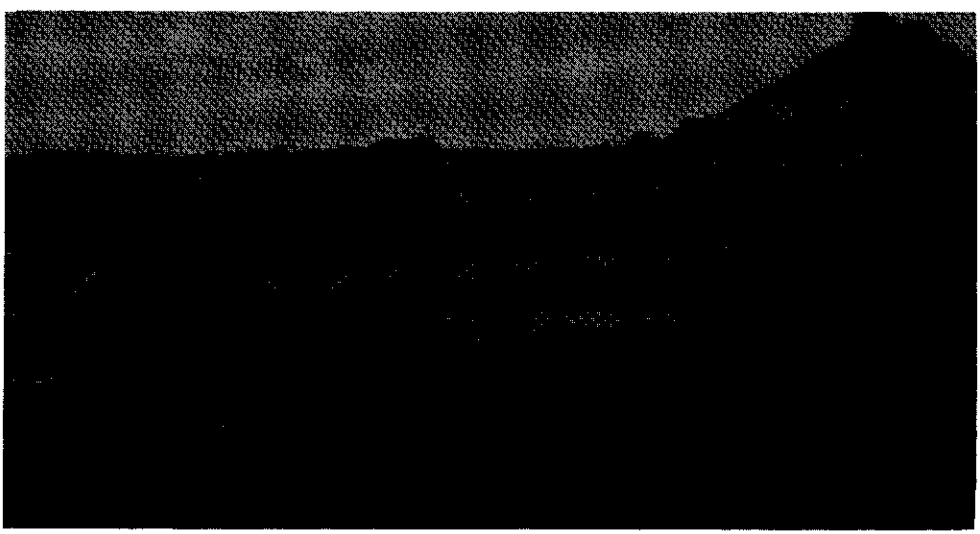


Figure 7.1. Example of erosion in an Alfisol field.

7.2. Occurrence of Erosion in Red Soils

Rainfall in the semi-arid tropics enhances detachment and transport of soil through its uneven distribution and high intensities. In periods with concentrated rainfall percentage of runoff increases. The higher the intensity of a rainstorm, the higher its kinetic energy (Wischmeier *et.al.*, 1958) which causes more destructive impact on the surface aggregates. Because of the low infiltrability of the red soils, an appreciable part of the rainfall during intense showers will run off after the available depressions have been filled, transporting the detached soil particles. Erratic distribution of the rainfall could mean heavy rain in the early part of the growing season, when the fields are still unprotected. But also prolonged wet spells could be expected, with continuous rain on a saturated profile. In both such situations, soil loss rates could be high. It is clear from many tropical situations, that a major part of the annual soil loss takes place during a restricted number of rainstorms.

In the view of Pierce *et.al.* (1983) the decline in productivity of red soils by erosion (referred to as "eroding productivity"), would take place as conceptualized in figure 7.2. for deep (B) and for shallow (C) soils. Specifically in the shallow soils, there is an urgent need to restrict the soil loss to a minimum. "Acceptable" soil loss levels are of the same order as the rate of annual soil formation, thus maintaining a balance in profile depth and -quality (Schertz, 1983). Long term improvement of many of the red soil areas could only be achieved by keeping the soil loss at still lower levels.

Reported soil loss figures for red soils show a wide variation over the years. The validity of such data also depends on the method of observation. Soil loss figures as available for Alfisol areas near Hyderabad, India, are

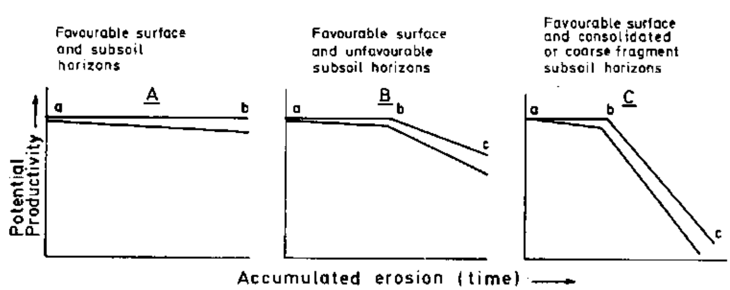


Figure 7.2. Concept of eroding productivity.
Derived from Pierce and Larson (1983).

estimated on the basis of water samples collected manually during runoff. As a 4-year average figure Vijayalakshmi *et.al.* (1982) report a soil loss of about 2.5 t/ha for differently cropped fields. At ICRISAT-station, for watersheds of about 4 ha a slightly lower mean figure (2.2 t/ha) was observed during a 4-year period, over the years ranging from less than 1.0 up to 3.5 t/ha (ICRISAT, Reports of work). These figures give an indication of the level of soil loss from such areas. But the inaccurate measurement technique (handsampling) as well as the location of sampling (at some distance downstream of the field) suggest that in the field itself the actual erosion might even be more serious. This suggestion can be verified in contour-bunded fields, by observing the rate at which freshly-made borrow-pits are being filled up. An often quoted period of four to five years would correspond with an average deposition of 40 to 50 t/ha per year. Under such conditions one may speak of a high level of "internal" sediment yield, occuring simultaneously with a much lower "external" soil loss.

7.3. Qualitative Aspects of Soil Erosion

Apart from the amount of soil transported within the field or leaving the field, its composition should also be considered. A comparison was made between the texture of the top soil of a 4 ha watershed and the texture of material sedimented in a reservoir directly below its outflow point *(table 7.1.)* (Pathak, personal communication). In this lay-out all watershed runoff entered the reservoir without passing a sand trap. The much finer texture of the material deposited in the reservoir is explained by a higher erodibility of the fine fraction and preferential sedimentation of the coarse material on its way towards the watershed outflow point.

The washing-out of finer particles during the erosion process can also be illustrated with data obtained from the 10 x 4.5 meter runoff plots at ICRISAT station, described earlier *(Appendix 9)*. In these measurements a separation is made between the soil that was caught in the sediment trap at

Table 7.1. Particle size distribution (%) of in situ and sedimented soil

	Size class (µm)				
	< 2	2-20	20-200	200-2000	> 2000
Topsoil Watershed	18	6	24	46	6
Tank Bottom	63	22	11	2	2

the end of the plots and soil particles that remained in suspension in the receiving barrels. Of the latter, a good estimate could be obtained of the quantity involved by taking water samples from the collected runoff. Suspended material was allowed to settle and was dried and weighed. Plotwise, however, this yielded too little material for a texture analysis. This was done by pooling samples collected up to August 7 and a second set from August 13 onwards. The particle size distribution of both trapped and suspended material was determined by the hydrometer method (American Society for Testing and Materials D 422; Bouyoucos, 1961). The analysis of the two combined samples from the suspended material shows the extremely high representation of fine particles, particularly during the earlier part of the season *(table 7.2.)*.

The texture of the eroded material was compared with that of the original top soil. This was done by calculating the ratio of the percentage clay plus silt (fraction < 50 µm) in the trapped and suspended material to the percentage < 50 µm in the top soil. This ratio is also referred to as "dispersion coefficient" (Kowal, 1970 b) and can serve as an indicator for the selective erosion. If we suppose a similar composition within both fractions < 50 µm, their ratio indicates the amount of top soil involved in the erosion processes[+)].
For the material caught in the sediment trap, this ratio was slightly above 1.0, with a maximum of 1.6 shortly after cultivation *(figure 7.3.)*.

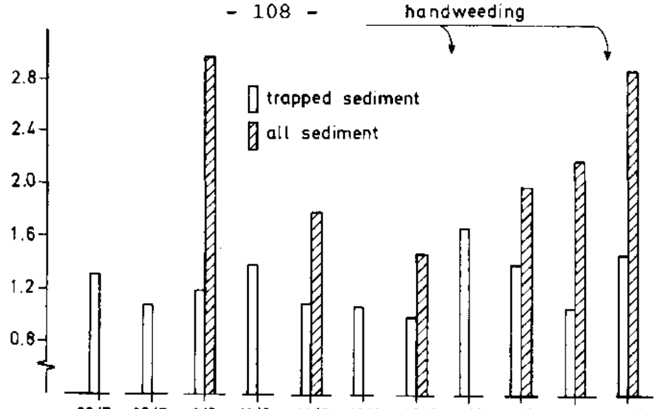
Table 7.2. Average texture of top soil, trapped sediment and material in suspension for two periods during the growing season (%). (RW-3F, 1980).

	Size class (µm)					
	< 2	2-20	20-200	200-2000	> 2000	< 50
Original top soil	10	6	28	48	8	18
<u>Before August 7:</u>						
trapped	18	4	21	53	4	24
suspended	59	27	13	1	0	93
<u>After August 13:</u>						
trapped	19	5	23	50	3	26
suspended	48	18	13	21	0	73

+) A related index was used by Lal (1976): the Erosion Ratio, defined as:

$$\frac{(\text{silt + clay})\ \%}{(\text{gravel + sand})\ \%}\ (\text{sediment}) \ / \ \frac{(\text{silt + clay})\ \%}{(\text{gravel + sand})\ \%}\ (\text{field soil})$$

This Erosion Ratio indicates the same tendency, but cannot be directly used to calculate the amount of top soil involved in the process.



Date	23/7	30/7	6/8	13/8	14/8	19/8	20/8	2/9	3/9	6/9	18/9
Storm size (mm)	34	23	22	13	13	118	56	30	20	30	12
Weighed Mean Intensity (mm/h)	110	24	24	21	21	29	25	152	25	31	12
Material in suspension (g/l)			3.5		1.6	0.8	0.9		2.2	3.5	4.7

Figure 7.3. Dispersion co-efficient (fraction < 50 µm in sediment/fraction < 50 µm of original top soil) over the growing season for small runoff plots (RW-3F, 1980).

However, if we include the material in suspension, ratio's were often higher than 2.0 *(figure 7.3.)*. Therefore, suspended material has a great influence and should always be included in such considerations. In our experiments data on the composition of suspended outflow was scarce, but the tendency is clear.

Both ratio's depicted in figure 7.3. are marked by a rise after hand weeding. This effect is caused by an enrichment of the exposed surface with erodible, fine fractions, partly through mixing of the surface layer, partly by the breaking up of relatively stable aggregates. A cultivation creates a less protected surface, more susceptible to the impact of raindrops. This trend was the same for the different surface configurations that were compared in the experiment and data for figure 7.3. are therefore lumped over the treatments.

Actual values, however, differed is so far as the values for the dispersion coefficient of the trapped sediment that were obtained from the flat cultivated plot (treatment A) were consistently only 2/3 of those of the other plots. A possible explanation for this might be the difference in flow pattern between the treatments. The more concentrated flow in furrowed plots causes higher flow velocities and a higher representation of stable soil aggregates in the transported material, thus yielding the finer particles in the trapped material.

The distinct increase of the finer fraction in the eroded material immediately after a cultivation was also measured by Gilley *et.al.* (1976) in rainulator tests on 22 x 4 meter plots, in North Dakota, USA. For a sandy clay loam they observed an erosion ratio of 1.14 for untilled plots and

2.31 for 5-7 cm deep tilled plots respectively.

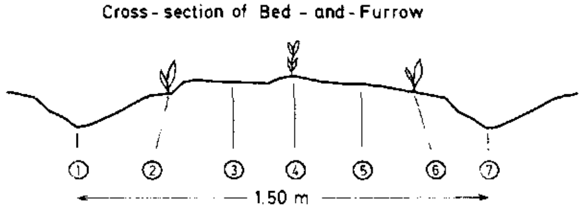
The height of the erosion ratio clearly depends on the presence of fine particles that can be removed. Other dependencies are difficult to prove. However, on basis of the available figures, and excluding the data obtained *immediately after handweeding*, there seems to be some correlation between the erosion ratio and the amount of runoff ($r = 0.27$) but no correlation at all could be observed with the intensity of rainfall ($r = 0.08$). This might support the assumption that the higher erodibility of the fine particles in these unstable soils is mainly caused by the "washing-out" effect of flowing water, these soils being dispersed already by the lowest raindrop impact[+)]. Zachar (1982) describes this phenomenon as laminar erosion. It is characterised by a low kinetic energy of the flowing water, washing away only the finest soil particles. Higher runoff amounts consequently would have a lower selective action. For an Alfisol, the result of such process is shown in figure 7.4. Soil samples from the surface, in the cross section of a bed-and-furrow, were analysed. The preferential removal of the finer fraction was greatest at those locations where surface flow concentrates, mostly in the furrows (location 1 and 7) and to a minor extent between the crop rows (locations 3 and 5).

7.4. The Influence of Field Characteristics on Erosion and Soil Loss

Topographic factors influence the processes of erosion and soil transport within a field. This is partly related to the difference in exposure of the topsoil to erosive factors; bedded fields are in this respect more erodible than flat cultivated fields, due to the ample presence of easily erodible strips, formed by the steeply sloping shoulders of the beds.

Surface configuration also determines the flow pattern of the surface runoff. Flow-velocity is a crucial factor as this influences the tractive force of flowing water, the quantity of sediment it can contain and the particle size it can move (Meyer and Monke, 1965). A higher flow velocity increases these capacities exponentially.

+) Yet, in soils with a higher aggregate stability, this will be different. There, higher levels of raindrop impact are needed to disperse the aggregates into erodible particles. This was explained by Meyer and Monke (1965) on the basis of observations in laboratory experiments, where raindrops induced splash and increased the turbulence of the runoff. This increased the sediment availability and runoff carrying capacity for small particles.



Location	Size class (µm)				
	< 2	2-20	20-200	200-200	> 2000
1	12	4	22	62	1
2	17	8	26	47	2
3	12	5	28	53	2
4	12	6	29	49	4
5	14	6	28	49	3
6	17	6	27	47	3
7	10	3	31	54	2

Figure 7.4. Particle size distribution (%) of top soil (0-1 cm) across a raised bed (RW-3F, september 1978).

However, this does not always imply a proportional increase in sediment content of the runoff water as, at some point, the forces that separate soil particles to be transported will generally become a limiting factor (Carson, 1971). Likewise the sediment content per unit volume of runoff decreases with an increase of duration of runoff, as reported by Ellison (1945) and Emmett (1970, cited by Carson).

Scouring action and transport capacity of the runoff can be minimized by keeping the flow velocity as low as possible. In an existing field, this can often be attained by reducing the slope in the direction of flow by construction of narrowly spaced furrows parallel or nearly parallel to the contour. Size and shape of furrows have an additional influence on the flow characteristics *(section 6.2.3.)*; in this respect wide furrows have advantages.

For a certain drainage channel, like a furrow, flow velocities also increase with a higher volume of runoff, be it less than proportional. Flow velocities can, therefore, be influenced by changing the size of the catchment area or its runoff production.
Local depressions, as can be encountered in flat cultivated fields *(section 6.2.1.)*, have a major influence on soil loss as they reduce the runoff quantity. In bedded fields a sedimentation of eroded material, and especially of its coarser fraction, is induced by a reduction of flow velocity

by the construction of low graded furrows. The ultimate effect on soil loss, however, appears to be different for the two situations and to depend on the height of the runoff.
Reduction of runoff and consequently soil loss, as caused by depressions in flat fields is, in relative terms, highest for low runoff events. On the contrary, for prolonged runoff its effectiveness decreases. And although reduction of flow velocity makes sense at extremely high runoff rates, to avoid scouring action, below such a critical value the concentrated flow in furrows makes the delivery of soil material to be transported the limiting factor in the process. With a higher intensity, therefore, soil loss from flat plots increases more than from bedded plots.

These effects can be shown on the basis of the already mentioned small plot experiments. The ratio of soil loss from the flat plots (A) and the furrowed plots (B) for individual storms could be related to their rainfall quantity and intensity *(Appendix, 9, figure A.2.(b))*+). For the low rainfall events with low intensities the measured soil loss from the flat cultivated plots was less than from furrowed plots. At higher runoff events, however, the opposite was observed.

Differences between treatments would be expected to even out if summarized over an entire season. Yet, in line with the small plot experiments, total sediment yield from flat cultivated field-scale areas was lower than from

Table 7.3. Runoff and soil loss from field scale plots (about 0.4 ha) for two surface configurations and two years

	runoff	soil loss	sediment content
	(mm)	(t/ha)	(kg/mm)
1979 (662 mm)			
Flat	89	0.4	4.5
	70	0.4	5.8
Beds	105	0.7	6.5
	87	0.7	8.5
1981 (1094 mm)			
Flat	224	3.8	17.0
	169	2.7	16.1
Beds	213	2.5	11.8
	309	4.7	15.3

+) Runoff from these plots was measured as volume, rather than as rate. As all reported rainfall events were runoff producing, it was assumed here that their intensities were also reflected in the intensities of runoff.

bedded areas in a year with well-distributed rain (1979) while is was not for a much wetter year (1981) (*Table 7.3.*). The differences in average sediment content of the runoff for the two years are even more illustrative.

7.5. Agronomic Practices to Reduce Erosion and Soil Loss

Keeping in mind the causative factors of water erosion and soil loss, *i.e.* the destructive impact of rainfall on the soil surface, the scouring effect of flowing water and the transport capacity of runoff, agronomic practices should be directed against these effects. Efforts, therefore, should be made to maximize infiltration and to protect the surface against the erosive influences of rainfall impact and flowing water.

In red soils, that have an inherent lack of structure, tillage has an important role to play. Its positive influence on infiltration, discussed in section 6.1.1., helps to reduce erosion. Heavy runoff, however, can reverse this effect. Following heavy rains, increased soil loss might be encountered from freshly tilled areas compared to areas with an undisturbed surface. Fortunately, the probability of heavy and continuous rain is highest in the latter part of the rainy season, during the period of full canopy development.

An important approach to combating erosion is the combination of all practices that establish a well developed crop before the periods of most aggresive rainfall. Within this scope, one should think of the choice of suitable crops or crop combinations, selection of suitable varieties and fertilization, and also of appropriate techniques and implements for caring for the crop. Mulching could be an outstanding method of providing more protection and reducing soil transport. But, as mentioned earlier, availability of suitable materials will generally be an insurmountable problem. For this reason, trials with mulching were not carried out.

CHAPTER 8 RUNOFF COLLECTION

8.1. General

With the alternation of too wet and too dry periods of the semi-arid tropics within a growing season, one obviously considers the possibilities of transferring excess water during a wet period to a subsequent period of water shortage. If the soil profile has insufficient storage capacity, this could be done by collecting and storing runoff water in a constructed reservoir. Required lay-out would furthermore consist of field outlets, waterways connecting to the reservoir and a spillway.

As a warning against simplifying the picture, Krimgold (1945) has already made it clear that a primary consideration in the design should be the dependability of the water inflow, with the proper and full utilization of that water next in line. The reservoir capacity should therefore be based on the inflow that can be expected to occur during the majority of years. This assures a certain availability of water and an economic use of the lay-out. Storage capacity might be still lower in some relatively wet areas, if an optimal use of water is already envisaged at lower volumes. Under semi-arid tropical conditions, of all soil types, red soils might be the most qualified for a runoff collection system, because of their high runoff generating nature and their generally low profile water retention capacity, which makes them drought sensitive.

8.2. Reservoirs: Design, Seepage and Evaporation

A large catchment area and a downstream water use allow for a flexible selection of the reservoir site, generally a valley that can be dammed. Alternatively the reservoir has to be constructed within the agricultural

part of a watershed. If this is the case it should be constructed by excavation, using the excavated soil for the embankment. Although a depression or piece of low quality land is preferable, more often than not the construction will be at the cost of productive land.
Where land is in short supply, a design with a maximum storage/area ratio is crucial. Moreover, to minimize earthmoving, a maximization of the storage/ excavation ratio should be pursued. This could be done by locating the reservoir at some distance below the outflow point of its catchment area, allowing runoff water to enter the reservoir via a raised channel. (Sharma and Helweg, 1982; Burton, 1965).

The effective capacity of a reservoir, defined as the volume of water ultimately available for irrigation, also depends on the level of water-losses, which take place through seepage and evaporation. As both loss-factors are continuous processes, the duration of storage is an important determinant. For a certain volume stored the shape of the reservoir determines the area over which seepage and evaporation take place. This area has the lowest value for a reservoir with a spherical shape.

Pepper (1976) studied a number of earthen dams, concluding that seepage through them is governed by a relatively thin sealing layer of soil at the boundary of the excavation. Such seals develop as suspended clay is carried in the seepage water, blocking the soil pores. The seepage rate is furthermore related to depth of water, exerting the pressure height. In line with the observations by Pepper, Alfisols and probably most other red soils do have some good properties that help avoid extremely high seepage rates. The low percentage of clay, mostly kaolinite, avoids the formation of cracks upon drying, so that the surface remains in good shape over the dry season. Through siltation of fine silt and clay particles and the washing-in process into the sandy structure, permeability of bottom and sides is reduced considerably in the course of a few years as was observed at ICRISAT-station and also reported by Vijayalakshmi (1982) for 2 other locations in India. Seepage rates, however, could still remain too high if no additional measures are taken. Most techniques to attain this are, regretfully, either too expensive to apply or prove to be insufficiently effective. Cluff (1981) lists a number of seepage control measures including chemical treatments, use of bentonite, soil cement, synthetic membrames, concrete and asphalt lining. From his projection it is clear that all such treatments are still undergoing further research as all have their specific problems, be it durability, availability of material or skill, apart from the costs involved. Research on cheap sealants, mostly mixtures of soil with cow dung or cement show meagre results (Vijayalakshi, 1982). Incidentally, percolation rates can be reduced considerably, but a major problem seems to be the maintainance of the lining over the years, following a number of wetting and drying cycles. Use of sodium-carbonate to reduce percolation (Reginato, *et.al.*, 1973) is well-known and often considered as a cheap and efficient method, but its usefulness is based on dispersion of clay and therefore less applicable in the sandy Alfisol areas.

On the same lines, reduction of evaporation from the reservoir is difficult to attain. Methods to achieve this through the application of reflective floating material or surface films of oil or fatty alcohols are costly and unstable because of wind action. Use of mechanical covers might be more promising from a technical point of view, but prove to be far too expensive for agricultural use (Cluff, 1981; Nicolaichuk, 1978). The single feasible approach to keeping evaporation losses at the lowest, would be to minimize the surface area of the reservoir. In a more advanced lay-out, this could be idealized in a compartmented reservoir (Cluff, 1979; 1981), where, after the rains have stopped, stored water is concentrated in a decreasing number of compartments by pumping. Such a system could probably be feasible in situations where water is required throughout the rest of the dry season for livestock or other intensive uses.

Specifications for the construction of reservoirs should be followed in respect to the allowable slope of the sides and compaction of the dykes that are related to material constants, being the local soil characteristics in the case of a dug-out, unlined, reservoir. Sufficient free-board should be allowed in order to avoid breaches through wave-action caused by flood flows or wind. In this respect, it is important that spillways are designed at the right location and with sufficient capacity. Carreker (1945) warned already that "inadequate spillways have probably more often been the cause of pond failure, than has poor dam construction". Detailed description of small dam- and reservoir construction can be found in several publications, including Kieft (1973), Soil Conservation Service (1977; 1981) and Costa *et.al.* (1983). For reservoir construction that includes the use of lining material, reference is made to Costa *et.al.* (1981; 1982) and Mueller and Karunaratne (1982).

8.3. Location of Reservoir

In deciding upon the construction of small surface reservoirs conflicts might arise in respect to the size and location of the reservoir, which are partly related to their intended use. A major controversy exists over which area in a watershed is going to benefit from the collected water. From a physical point of view it would appear most logical to design a cascading series of reservoirs, where water collected from the one area is to be used for irrigating the adjacent lower stretch. Application of water could be done via a gravitational lay-out. Size of the reservoir and its contributing area could be chosen on the basis of technical, topographical and organizational considerations, which would generally favour the construction of a smaller number of larger reservoirs, reducing the construction costs per hectare, and lowering evaporation and percolation losses by a lower wetted surface/volume ratio. Realising the mostly small land holdings in India, such lay-out would involve a number of farmers per reservoir. It would therefore divide the ownership of the water and that of the land from where the water is collected. If the farmer in the water generating area is not the same person who owns the field benefitting from it, he might be reluctant to co-operate in a proper lay-out and maintenance of the system. But even if both the contributing and benefitting part of the watershed were farmed by the same person, the risk of the farmer neglecting water conservation measures in the upper part would still exist. As a matter of fact water conservation in his upper field would go at the cost of water availability in his lower area. This attitude could be aggrevated by differences in land quality.

A different system would result from a scheme in which collected water is used in the area it originates from. Consequences related to the size of the system in respect to construction costs and water losses would be similar to those mentioned for the cascading system. Application costs of the water would be higher as lifting of water is required. If, however, the area of such system is kept very small (say 0.25 - 0.50 ha), a completely different picture of water collection and utilization emerges. Now, for a farmer, the possibility of recycling water is created, which is evidently supplemental to his efforts to conserve rainfall in the same field. He would, therefore, be in a position to implement techniques that are both aiming at the best field practices for conserving water *in situ*, and at a good and efficient surface drainage and water collection. As the collected water is at his own disposal, this would lead to most efficient field application methods and it could easily be anticipated that the availability of water close to the field would lead to an earlier and more frequent use of it. This is also more likely in view of the higher collection efficiency for such small catchment areas, resulting in an earlier and higher availability of stored water *(section 4.5.)*.

8.4. Use of Collected Water

As outlined in section 8.3. a choice, concerning size and location of a reservoir could be made, roughly speaking between a small reservoir serving an individual field and a higher capacity reservoir collecting its water from a much larger (sub-) watershed area. To a large extent such a choice would be based on the anticipated utilization of the water. In field scale reservoirs, collected water would be used in the first place for supplementary gifts during dry spells in the rainy season. Larger reservoirs would serve to collect water mainly to extend the growing season or to enable the growing of a post-rainy season crop.

Local mean rainfall and its distribution and soil characteristics are important physical parameters at the base of such a choice. The rainfall pattern of Hyderabad, India alone would still leave this choice open, as the probability of a prolonged dry spell is not extremely high (Kampen, 1975). Concerning soil characteristics, shallow Alfisols would bias the choice towards field scale reservoirs, as they are already sensitive to short dry spells with a higher probability of occurence, while for deep Alfisols the option for larger reservoirs would appear to be more appropriate, providing water for a sequential crop, as a supplement to the profile-stored water. *(Compare figures 4.1. - 4.3., section 4.5.).*

Using collected water in the first place for supplementary irrigation during the rainy season limits the required capacity of the reservoir to a level that is based on the runoff expected during the period prior to an expected dry spell. On the basis of this constraint its capacity could be in the order of 350 - 400 m^3/ha for Hyderabad conditions, based on an average of 10 - 15% runoff during the first half of the rainy season. This quantity of water would be sufficient to supplement the profile water for at least one week, if efficiently applied. Refilling of the reservoir can be expected before the end of September, more so because runoff percentage is higher later in the season (15 - 20%). This water could either be used for another supplementary irrigation before maturing of the rainy season crop, if possible and thought necessary, or for a sequential crop. Possibilities for such use would include an irrigation to stimulate ratooning, irrigation of an intercrop component or a series of water gifts of a sequential crop on part of the area.

Incidental experiences with small water gifts at ICRISAT reveal the impressive yield increases that could be attained. All observations, however, refer to deep Alfisols. Therefore, in several other years no supplemental water was needed during the rainy season, when the profile provided sufficient buffer capacity, which may not be expected for shallow soils. Yield advantages due to irrigation of a rainy season crop were reported for 2 years *(table 8.1(a))*[+)]. For two further years ICRISAT reports positive results with application of small water gifts on Alfisols in the post-rainy season. *(Table 8.1(b))*.

Leaving aside the data on pearl millet and sunflower the water utilization efficiencies for both rainy season and post-rainy season supplementary irrigation proved to be high.

Table 8.1: ICRISAT's observations on yield effect of supplementary irrigation on deep Alfisols.

Year	Crop	Water gift	Yield		W.U.E.[+)]
			control	irrigated	
		(mm)	(t/ha)	(t/ha)	(kg/ha. mm)
(a) Rainy season					
1973 - 1974	Sorghum	2 x 50[x)]	4.87	5.25	8
	Pearl Millet	2 x 50[x)]	3.34	3.48	0
	Sunflower	2 x 50[x)]	1.12	1.33	6
1974 - 1975	Sorghum	1 x 50	2.76	3.29	11
	Sorghum	2 x 50		3.87	11
	Pearl Millet	1 x 50	2.89	2.87	0
	Pearl Millet	2 x 50		2.95	0
	Sunflower	1 x 50	0.65	0.74	2
	Sunflower	2 x 50		0.76	1
	Maize	1 x 50	4.08	4.47	8
		2 x 50		5.00	9
(b) Post-rainy season					
1975 - 1976	Tomato	2 x 25	12.5	23.4	200
	Safflower	1 x 25	1.04	1.38	13
1977 - 1978°)	Sorghum	75	0.18	0.83	9
	Sorghum	100		1.37	12
	Sorghum	200		1.57	7
	Ratoon Sorghum	75	1.17	2.02	11
	Ratoon Sorghum	100		2.31	11
	Ratoon Sorghum	200		2.57	7

+) Water Utilization Efficiency, defined as the harvested yield per unit of water. (Doorenbos and Kassam, 1979).
x) Second water gift was immediately followed by 37 mm of rain.
°) No details about distribution of water gifts available.

Sources: ICRISAT (1974; 1975; 1976; 1978)

+ In a different location at ICRISAT-station a single 50 mm water-gift on August 23, 1974, resulted in an impressive increase of yield from 2,960 kg/ha to 5,750 kg/ha for maize (Krantz, personal communication).

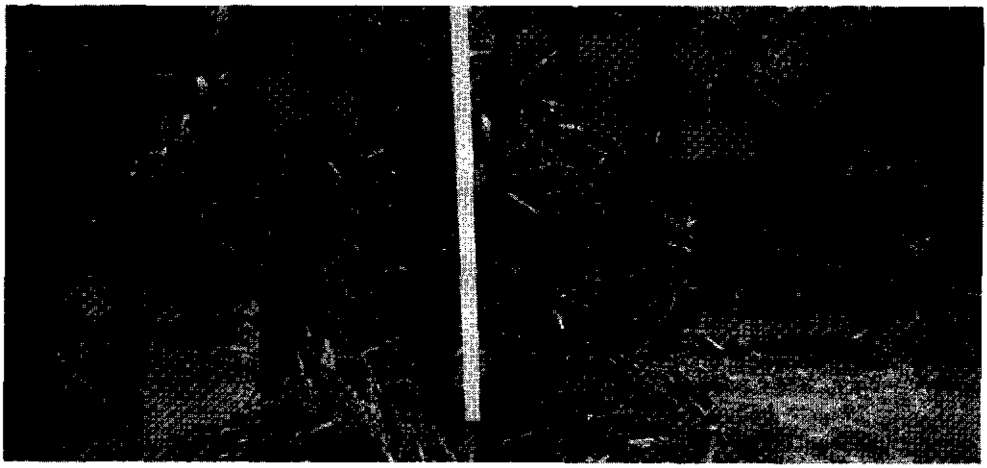


Figure 8.1. Little water may have impressive effects (supplementary irrigation of sorghum).

These figures compare very well with expected efficiencies for irrigated agriculture, as given by Doorenbos and Kassam (1979) *(table 8.2)*.
Quantities of water required for post-rainy season irrigation will be higher than for rainy season supplementary irrigation. Consequently, if it is chosen to irrigate post-rainy season crops, larger size reservoirs are needed that are able to store total season's runoff. Estimated maximum capacity would be in the order of 1100 m^3/ha under Hyderabad conditions, based on a mean runoff percentage between 15 and 20 at a total seasonal rainfall of 600 mm.

8.5. Availability of Water over Time

In the case of water collection with envisaged use during the post-rainy season, duration of storage of at least part of the collected water is

Table 8.2: Water Utilization Efficiences (W.U.E.) as obtained under optimal conditions in respect to crop- and watermanagement

Crop	W.U.E.
	kg/ha. mm
Sorghum	6 - 10
Sunflower	3 - 5
Maize	8 - 16
Tomato	100 - 200
Safflower	2 - 5

Adapted from Doorenbos and Kassam (1979) relatively long, resulting in high losses through percolation and evaporation. Together with inevitable application losses and a subtraction for dead storage, it will be clear that in most situations only a part of the runoff-contributing watershed can benefit from the collected water. Yet, such a system does allow for more concrete planning than a system oriented at supplementary irrigation of rainy season crops, as distribution of runoff over the season hardly affects the total water-availability by the end of the season. Furthermore, a reservoir that was not completely full would still allow for a proper use, be it on a reduced area.

Aiming at irrigation during the rainy season, a smaller reservoir would be designed allowing a certain level of overflow in some or most of the years. This, however, would mainly happen in the later part of the season. The reservoir should be able to retain sufficient water in the first half of the growing season.

The change in storage of water in a reservoir (Δ S) at a chosen interval can be computed according:

$$\Delta S = Q + P - E - D - I_x - O \qquad (8.1.)$$

with: Q = inflow

P = Precipitation

E = Evaporation

D = Percolation

I_x = Water extraction for irrigation

O = Overflow

which should all be expressed in m^3.

Storage at the end of the interval i (S_i) equals:

$$S_i = S_{i-1} + \Delta S \qquad (8.2.)$$

Kramer (1974) presented a method of analysis to arrive at a failure probability, defined as the chance of depleting a reservoir at too early a stage, based on long term rainfall/runoff data. His calculations are directed towards a situation where the period till the next inflow has to be bridged with a predetermined required volume of water. Assuming a flexible water requirement, which would be determined by actual shortage and would be partly adjustable via crop choice and size of area irrigated, a much more complicated picture would result from such analysis.
Following equation 8.1 a much simpler calculation of in- and outflow components of a reservoir resulted in figures 8.2 and 8.3.

Figure 8.2 gives the calculated stored volume of water in a reservoir with

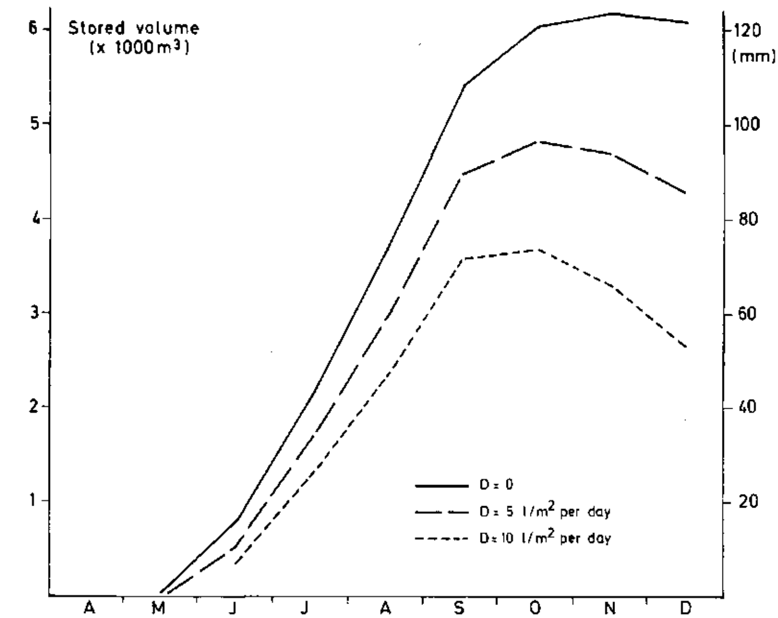


Figure 8.2. Calculated stored volume of water for a 5 ha watershed reservoir, aiming at post-rainy season use, and for different rates of percolation (D).

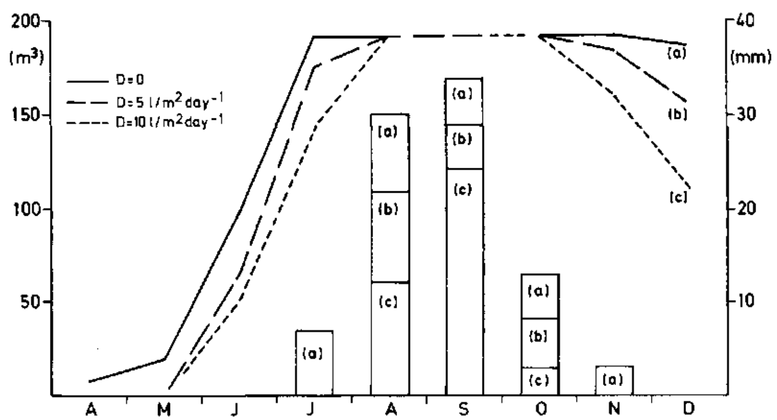


Figure 8.3. Calculated stored volume of water (lines) and volume in excess of reservoir storage (bars) in a 0.5 ha field reservoir, aiming at supplementary irrigation during the rainy season, and for different rates of percolation.

a 5 ha catchment area in the course of a rainy season. Figure 8.3 gives these figures for a "field-scale" reservoir with a capacity of 192 m^3 and a catchment of 0.5 ha. The figures are based on mean monthly rainfall for Hyderabad, runoff percentages assumed at an average of 15 and 20% for the first and second half of the rainy season respectively and an evaporation from the reservoir equaling 90% of pan evaporation figures. As stated earlier, a smaller area will yield more runoff than a larger catchment. For comparitive reasons, the figures 8.2 and 8.3, however, are drawn on the basis of the same runoff yield, irrespective of the size of the catchment area.

In both figures, line (a) assumes that no seepage occurs, so that the reservoir losses are restricted to the evaporation component. Lines (b) and (c) refer to similar reservoirs with a seepage rate of 5 (lines (b)) and 10 (lines (c)) l day^{-1} m^{-2} respectively for their submerged areas.

In accordance with the anticipated use of the smaller type, water for irrigation is available in August, which could deplete the reservoir. This is made up by subsequent inflow.

Seepage and evaporation constitute the losses from storage in these unlined reservoirs. Their effect over the period of storage can be visualised by indicating the ratio of available water at a certain moment to the volume of inflow till that time, denoted as the efficiency of storage *(Figure 8.4. (a) and (b))*.

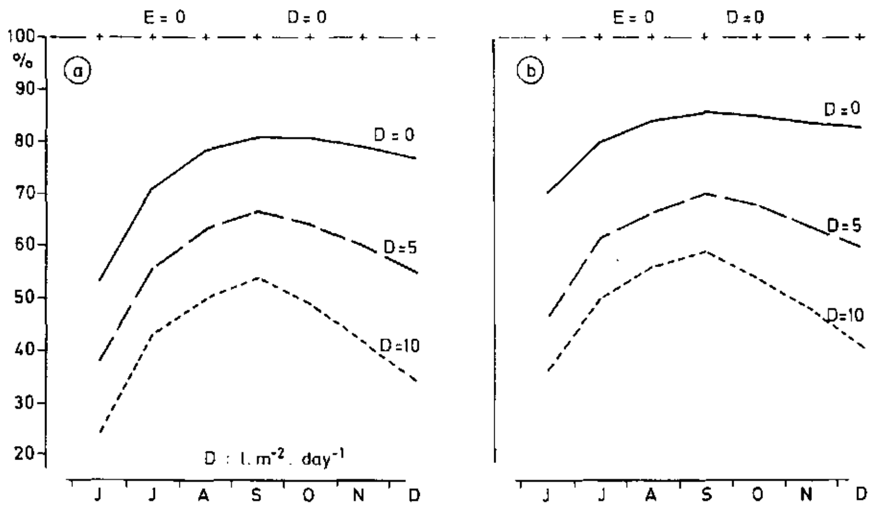


Figure 8.4. Efficiency of storage (volume of available water as percentage of the total inflow till date) over time for assumed levels of seepage (D): (a) watershed scale reservoir with sufficient storage capacity to collect total expected season's runoff (b) field scale reservoir, with restricted storage capacity and with use of water or overflow during the rainy season. (E = Evaporation).

In the case of the field-scale reservoir, available water constitutes the volume of stored water plus the amount of water indicated as excess water in figure 8.3., assuming that this could have been used for irrigation. In figure 8.4., the three curved lines represent the storage efficiencies resulting from reservoirs with seepage rates of 0,5 and 10 mm/day respectively. Evaporation (mm/m^2) is taken as an un-reduced rate for these three cases, related to pan evaporation.

The low storage efficiency for the larger reservoir in June and July is due to the relatively extended surface area of a small volume of water stored and the resulting high losses. Seepage from the larger reservoir, when filled, is lower than from the smaller reservoir per unit of volume stored, because of a more favourable storage/wetted area ratio. The apparently higher storage efficiencies later on for the smaller reservoirs are influenced by the inclusion of the excess water component, supposedly used for irrigation. This water is not stored and does not contribute to the losses.

It appears that for the larger reservoirs with a low seepage rate of 5 mm/day, about 20% of the orginally stored water is lost by seepage during the period June up to November, similar to the volume lost by evaporation. As the period of irrigation from such a reservoir can be anticipated, so can expected losses by seepage. A comparison between the costs of seepage reduction and the benefits of the water saved, is made relatively easily for a specific situation, as the latter is mainly based on a water-yield relation.

Benefits of lining the field scale reservoirs are more difficult to predict. While, in the first half of the monsoon season, seepage per unit of volume stored is lower than in the larger reservoir, lining could further reduce it. Its benefits, could be high if the lining helps in making sufficient water available to bridge dry spells, reducing the risks of complete crop failure.

8.6. Construction of Reservoirs

In India the construction of un-lined reservoirs could be executed at relatively low costs. If done largely by hand, most of the costs involved would be for labour, which has a low opportunity cost, if the work can be executed in a period without much agricultural activity. ICRISAT's experience has taught that, in an Alfisol area, the construction of a 5,100 m^3 tank could be done at the cost of Rs 0.95[+)] per m^3 storage (ICRISAT, 1978).

Construction costs of reservoirs not only depends on the availability of labour and/or equipment, but also on the alternative use of the occupied land and on labour and material required for auxiliary structures. Seepage reduction can be achieved by a variety of measures, varying in efficiency and costs involved. They are location specific, as they depend on the local availability of required material and skill.

Costs of reservoirs should also be seen in relation to the frequency of use of the created storage capacity. In a situation where water is used exclusively some time after the rain has ceased, the volume of water, available for irrigation, is less than the storage capacity of the reservoir. Its frequency of use is, therefore, always less than one per year. If, however, water from a reservoir is already used during the rainy season, allowing the reservoir to fill up again, the frequency of use of the created volume increases.

Table 8.3. Details on two differently sized reservoirs

Type of reservoir		Watershed	Field
Catchment area	(ha)	5.0	0.5
Reservoir volume+)	(ha. mm)	122	38
	(m^3)	6,099	192
Surface area reservoir	(m^2)	1,810	133
	(%)	3.6	2.7
Area of sides + bottom	(m^2)	2,038	161
Volume/Wetted area	(m^3/m^2)	2.99	1.19

+) Calculated on the basis of an inverse cone segment, with side slopes 1 : 1, and radius at bottom and top of 4.5 and 6.5 meters respectively for the field-scale reservoir, 20 and 24 meters resp. for the watershed-scale reservoir.

In table 8.3 some technical details are given, referring to the two reservoir systems discussed earlier. Construction costs of such reservoirs per m^3 of water ultimately used, depend on a number of factors. Denoting the costs for earth moving as "x" per m^3, for lining as "y" per m^2 and for auxiliary structures as "z" per m^3 storage, the total costs per m^3 of water used can be approximated by:

+) 1 US$ = Rs 10/-

$$\left(\frac{1}{a} \cdot x + \frac{1}{b} \cdot y + z\right) \cdot \frac{1}{c} \qquad (8.3.)$$

with a = storage/excavation ratio of the reservoir

b = ratio of reservoir volume versus wetted area

c = frequency of use per year

In a comparison between the two reservoirs, we may assume a similar value for the factors a, x, y and z. The value of "b" (volume/wetted area) would be lowest for the smaller reservoir, but this might be made good by a higher "c"-value (frequency of use). If so, this makes the two systems similar in ultimate water costs. If we assume the costs of earth moving at Rs 1/- per m^3 and that of lining at Rs 10/- per m^2, this would result in a cost of Rs 6/- per m^3 of water, excluding the costs of auxiliary structures.

Such costs seem to be compatitive with the costs of water in many irrigation systems, while the observed water use efficiencies also compare favourably.

CHAPTER 9 ASPECTS OF WATERSHED DEVELOPMENT AND MANAGEMENT

9.1. General

In its commonly used definition a natural watershed from ridge to outflow point could cover an appreciable area of land and would generally include a range of soil-types or -qualities, vegetation and land-uses. In the toposequence or catena of such watershed one would consequently expect to encounter a range of human activities. Simplified, a toposequence for semi-arid tropical areas could be indicated as a (natural) vegetation of trees, shrubs and grasses at the top, an agricultural part with rainfed crops in the middle and economically higher valued crops in the lower and wetter part of the watershed, possibly irrigated.
From an hydrological point of view this sequence would coincide with a water-recharging area, water-transmission area and a water-discharging area respectively.
Geologically seen these zones are characterized by a decreasing level of erosion and increasing sedimentation.

The middle part of a watershed is the area that is normally used for rainfed agriculture, that is (or could be) under permanent cultivation of annual crops without being supplemented by inflow of water in addition to precipitation. It has higher agricultural potentials than the upper reach of the watershed, but is far more susceptible to the vagaries of nature (resulting in erosion and droughts) than the lower area.

In a rolling type of landscape, as is very common in semi-arid India, (relative) topographic heights and depressions exist within this agricultural zone. By these height differences sub-watersheds are formed within the potentially cropped area. These could be denoted as agricultural (sub-) watersheds, as is common in the vocabulary of ICRISAT.

Agricultural (sub-)watersheds are restricted in size and none of the forementioned divisions in zones can be made. In the area studied aquifers are almost absent and percolation and sub-surface flow of water will mostly be irrelevant for the concerned area. Its hydrological behaviour can be described with factors that are related to precipitation, profile storage and surface runoff, with percolation as a loss-factor. Because of the exclusion of the subsurface flow component it is possible to change the area of an agricultural watershed by adjusting the surface drainage pattern. This could be done, aiming at creating a more homogeneous or better shaped area or at subdividing the area in order to lower the runoff volume or peak flow. It could be an unintended consequence of the construction of runoff obstructions like a reservoir or a road. This way agricultural watersheds become more or less artificially created units.

Under conditions of subsistence farming a watershed area would have to support a community of people in most or all of their basic requirements, which include such necessities as a place to live, water supply, grazing land, arable land, fuel supply and infra-structure. Watershed development and management, therefore, are concepts that could imply a wide range of activities.

A well-balanced use of the natural resources of a watershed area as under traditional occupation, however, is not compatible with the increasing population densities, as have been occurring in many parts of the world and very distinctly in India. With an almost stable productivity on area basis, increasing requirements for food and introduction of cash crops could only be attained through extending the food-producing area to less suitable parts of the watershed. Increased demand for fuel has been depriving the natural vegetation of trees and woody shrubs. Increase in number of cattle and decrease of availability of grazing land has been causing overgrazing and deterioration of the land. Through all this the protection of land by natural or otherwise suitable vegetation has been diminishing, thus increasing runoff and erosion.

In this situation, there is an urgent need to take measures that will stop a further loss of the natural resources soil and water and that can possibly increase the productivity of the area.
Firstly, this requires an evaluation of the land, its present use and its potentials. A list of questions as given by FAO (1976) and supplemented by Beek (1978) could serve as a basis for a comprehensive land use planning:

- How is the land currently managed, and what will happen if present practices remain unchanged?

- What improvements in management practices, within the present use, are possible?
- What other uses of land are physically possible and economically and socially relevant?
- Which of these uses offer possibilities of sustained production or other benefits?
- What adverse effects, physical, economic or social, are associated with each use?
- What recurrent inputs are necessary to bring about the desired production and minimize the adverse effects?
- What are the benefits of each form of use?
- What changes in the condition of the land are feasible and necessary, and how can they be brought about?
- What non-recurrent inputs are necessary to implement these changes?

Such evaluation indicates the irrelevance of restricting oneself to the indication of suitability based on technical and soil-physical considerations alone. The actual use of the different watershed parts should serve as a guidance for planning. Within each catagory, then, improved practices should be recommended for further implementation.

9.2. The Zone of Recharge

Measures taken in the zone of recharge (the upper part of the watershed) should in the first place be oriented at inducing infiltration to provide more moisture for the local vegetation. This could be achieved both by improving the permanent vegetative cover and, until optimum growth is reached, by the creation of depression storage by engineering measures and land management. Infiltration beyond profile storage capacity may ultimately replenish the groundwater in the downstream area while it also further reduces the contribution to torrential surface flow over larger areas.

Additional interventions could be oriented at impeding runoff through measures like diversions and dams. These measures lower the soil transport capacity of the runoff water and reduce the inflow at lower stretches of the watershed. Under conditions of a well-developed permanent vegetation, runoff might be negligible in much of the semi-arid and sub-humid areas during most storms and even without additional measures (Kowal, 1970). Incidental storms, however, could still cause appreciable runoff, for which a safe disposal is needed.

In many situations, the upper part of a watershed is mainly destined as a source of fuel and as grazing land. Increase of production per unit area could often be achieved by proper selection of grass and tree species and proper care and protection of the vegetation. This requires a strong involvement of the users of the area in supporting development and avoiding renewed exhaustion. Problems may arise where such watershed parts are common property. An organizational structure is a pre-requisite to guarantee a permanent controlled use. To set conditions for such co-operation it should be ensured that the production capacity is high enough to satisfy the users, or that alternative sources are developed or provided to reduce the demand up to the level of the area's bearing capacity. Alternative sources could, for example, consist of an alternative energy supply or an increase of the fodder production at the agricultural parts of the watershed.

9.3. The Zone of Discharge

In the lower stretch of a watershed one may expect a higher intensity of agricultural activities, as the soils (through deposition) tend to be better than at higher elevations in respect to fertility and crop water availability. In many parts of India concentration of water in this area, both as subsurface flow and surface flow, enables the growing of irrigated crops, even such water demanding crops like rice and sugarcane.

The runoff collection and subsequent irrigation of a crop like rice seems, at least physically, to be a poor approach in a semi-arid tropical area given its low efficiency of water use compared to many other crops (Puttana, 1983). The higher and more secure yield per hectare, combined with a relatively cheap and easy to maintain lay-out, however, make such a system a profitable alternative over rainfed production and over irrigating other crops, for an individual farmer+) (based on the gross margin per ha or per m^3 of water).

In this situation, longer term effects on overall productivity and system's stability are not incorporated. The higher parts of a watershed function as the catchment for the lower parts. Improper management of the upper reaches will first of all increase runoff. This would seemingly benefit the lower area because of a higher water availability, but the related increase of peak-flows endangers the lay-out and may cause breaching of reservoir dams.

+) Data on reservoir supported rice production for a number of locations in Southern India, however, show a rapid deterioration of the system under the present conditions of management (section 4.2.4.)

Moreover, higher runoff increases the amount of soil carried by the water, particularly from poorly protected contributing areas, causing additional siltation in the reservoir.

Yet, reservoirs and wells in the zone of discharge depend on the inflow from the upper reaches of the watershed. Measures that change the hydrology of the contributing area, may clash with the interests of the irrigation systems. As far as water is recovered from wells, additional infiltration in the upper reaches will only be beneficial for groundwater replenishment but if the irrigation system is reservoir based, a reduction of inflow will have its impact on the availability of irrigation water. This is most relevant in watersheds where most or all of the catchment area consists of cultivated land.
In southern India, however, part of the inflow into reservoirs originates from rocky areas, so that runoff retardation in the cropped parts of a watershed will have little, if any, adverse influence on the irrigation system.

9.4. The Agricultural Watershed

9.4.1. General

On areal basis, the central zone of a watershed is generally by far the most important part for agricultural production. Although incidentally farmers may have a (small) piece of irrigated land in addition, most farmers of semi-arid India fully depend on their fields in this part of the watershed. Here we find the agricultural (sub-)watersheds that, apart from some exceptions, do not possess any form of additional water supply over the local rainfall.
A high variation of soil quality exists both interregionaly as intra-regionaly, and even within an agricultural watershed major differences in quality can be observed between fields, mainly related to their topographical location and level of erosion. Regional differences in rainfall quantity and its distribution add to the diversity in suitability for production of individual fields.

Commonly, the natural main surface drainage pattern forms the basis of a watershed lay-out. Individual agricultural fields, varying in size and of irregular shape fill up the whole area. They are separated from each other by small bunds or by other marks. Some parts, mostly of poor quality, are government-owned and designated as common grazing land. Shallow drainage ways frequently cross cultivated fields. Scattered trees and bushes may grow on pieces of bad land, alongside tracks and on bunds. Depending on soil quality and rainfall pattern different crops or crop combinations are grown, which also determine the level of use of manure and/or fertilizer. Loss of organic matter and nutrients through the washing-out effect of surface runoff could locally be high.

In many areas a drastic change in the watershed lay-out can be observed through the construction of contour-bunds. Through these bunds runoff water is partly held back and ponded in the field, partly routed into more or less protected drainage ways *(Section 5.3.1.)*.

9.4.2. Options for Development of an Agricultural Watershed

9.4.2.1. General

An overall watershed development plan should be based on the objective to increase the productivity of the concerned area at an acceptable level of stability and with due consideration for the technical, social and financial limitations met by the farmers. Stability of production over the years is a prerequisite for co-operation of subsistence farmers. Stability, however, also refers to the long term conservation of the soil resource which, due to their weak and uncertain economic position, is normally out of subsistence farmers's scope.

Watershed development, therefore, is an activity that, to some extent, goes beyond the direct responsibilities of the individual farmers and even the group of them. It rather concerns the regional or national authorities. An individual farmer, at the most, can be expected to apply techniques that are oriented towards the conservation of soil and water within his field. In a co-operative structure, he could be involved in the construction and maintenance of watershed bases activities, as long as this proves to be beneficial for his own production. However, activities that are not short term production oriented are not in the direct interest of subsistence-level farmers, who can not afford to invest in them.

Viewing the red soil areas in semi-arid tropical India, characterized by their sensitivity to drought and their high erodibility, two development approaches on land- and watermanagement seem to be available. The simplest approach would comprise only a minor adaptation of the traditional system of farming, but would be strongly oriented at runoff control from watersheds to stop further deterioration through erosion *(Section 9.4.2.2.)*. Such approach, however, also lacks potentials for distinctly increasing production.

The other approach would be based on the introduction of a renewed system of cultivation, aiming at an overall watershed development and protection, including water collection for supplementary irrigation *(Section 9.4.2.3.)*. The latter can be seen as the approach envisaged by ICRISAT.

9.4.2.2. Option 1: Protection of the Agricultural Watershed

From the foregoing chapters, it may have become clear that for the red soil areas and for small fields in particular, a system of flat cultivation can not always be considered as inferior to a system of bedded cultivation as experimented with by ICRISAT, under otherwise similar conditions. In respect to runoff and soil loss, flat cultivated fields may even be considered slightly superior to the bedded system, although this might not always be true in areas that are wetter than Hyderabad or in relatively wet years. *(Section 6.2.)*. Moreover, this difference might be removed by a more intensive tillage of the bedded plots *(Section 6.1.1.1.)*. As flat cultivated fields lack the provision of a controlled drainage system, problems, however, will arise in larger fields and with big runoff producing storms.

Another characteristic of flat cultivated fields is the presence of macro depressions *(Section 4.4.3.)* that could be the reason for waterlogging during wet periods, suffocating the crop and hampering field operations. At the same time, however, such depressions serve as temporary water storage, thereby reducing the runoff from many small storms, conserving water. A system of flat cultivation is traditional for India and is normally executed with extremely cheap implements+).

+) It should be noted here, that the reported comparisons between flat cultivated and bedded fields on runoff, soil loss and crop yield, are related to the surface configuration only. For the sake of comparison, use was made of improved implements for both systems. In referring to the system of flat cultivation as it is traditional for India, the use of traditional implements, local crop varieties and crop management is assumed.

Watershed improvement under these conditions and constraints, would be concentrated on an improvement of the surface drainage and runoff control, to make the best of the traditional techniques and to protect the individual fields. This can be arrived at by a number of measures:

- Individual fields should be restricted in size to avoid excessive flow within the field.
- The fields should be protected against inflow of surface runoff from higher areas.
- A proper choice of field boundaries is required, so that, to its maximum possible, the direction of one boundary coincides with the envisaged direction of cultivation (slightly off the contour) while another coincides with a natural drainage line, if present.
- Within the fields excessive water stagnation should be avoided by an appropriate levelling.
- Field runoff should be diverted to a protected waterway, avoiding prolonged stagnation in the field. If held back in the field for a short duration (say less than about 12 hours), this could be beneficial in repect to water conservation and reduction of runoff volume and peak flow.
- The total area under bunds (mainly to retard and divert runoff water) and waterways might go up to some 10% of the watershed-area. Bunds, therefore, should be made productive by growing trees on them.
- Main drainage ways should be protected by a grass vegetation or otherwise and, where necessary, provided with drop structures.

Development of an agricultural watershed on these lines is a minimum requirement for controlling erosion, but it has little improvement on the water availability for crop growth.

9.4.2.3. Option 2: Development of the Agricultural Watershed to Increase its Productivity

Production levels under traditional systems of farming are low and the measures that were discussed in the foregoing paragraph would hardly contribute to raising them. Introduction of improved varieties and fertilization would be restricted in such systems to the best soils, as insufficient profile depth creates a high risk of crop failure in drought periods.

The productivity of most of the red soils in the semi-arid tropics could only be distinctly increased and better secured if watershed development, apart from protection, includes the creation of water storage capacity in excess of that of the soil profile *(Section 4.5.)*. This could be done by the construction of small reservoirs in which runoff water is collected and that serve as a source for supplementary irrigation *(Chapter 8)*. Such lay-out, however, requires high development costs and should therefore be based on the use of improved varieties that have a high response to the improved water availability. Such varieties have to be supported by sufficient fertilization and optimal field conditions. The latter refer to a suitable and homogeneous topography and surface drainage, required to enable accurate and speedy operations and an early entry into the field after heavy rain. Where traditional techniques and implements can not guarantee such proper conditions, they have to be replaced by an adapted system. Experience at ICRISAT suggests that the use of a bedded surface configuration would be better able to provide these field conditions *(Section 6.2.)*.

For the development of an agricultural watershed the use of a bed-and-furrow configuration in the individual fields has several implications. The fields can be made larger than with flat cultivation as the presence of the furrows already provides sufficient safeguard against excessive concentration of runoff. Only the length of individual furrows should be restricted to say 60 to 70 meters. Although water stagnation in macro-depressions will be confined to furrows and not directly damage the crop, land levelling is still required as the water in the furrows would delay entry into the field. The number of bunds could be lower and their size smaller compared to flat cultivated areas and would not have any other function than as border and footpath.

In a watershed design it should be included that the slope in the direction of the furrow is restricted to a minimum, just allowing a free outflow of water. Practical experience has shown that a mean slope of 0.4% can be considered optimal, as at lower design values frequent backsloping would occur. Uniformity of shape and size of the bed over the field is another important aspect, necessary for an optimal performance of subsequent field operations.

The shape of the bed and the furrow also determine the depression storage capacity on top of the bed *(Section 6.2.1.)* and the flow characteristics of the furrow *(Section 6.2.3.)*. On the basis of experiments on 1.50 m wide beds preference would go to a shape with narrow furrows and a level bed, at least for Hyderabad conditions.

9.4.2.4. Tillage and Crop-Management

Although mostly restricted in its capacity, the soil profile remains a most important and efficient reservoir for storing moisture. However, adverse characteristics of the red soils often hamper infiltration, causing extra runoff and soil loss. More than the surface configuration, appropriate tillage could improve on this.

From different experiments measures to improve the water entry into the profile can be derived. These include an intensive primary tillage which increases the plough layer storage *(Section 5.1.1.1.)*. Although for the described system of intensive tillage the number of passes increases, the draft requirement for individual passes is nominal, at least in a bedded surface configuration. A similarly intensive tillage in flat cultivated fields, however, appeared to be impossible. Intercultivation to break the crust and to create a rough surface was found to conserve water, but its effects were of short duration and required an early repetition *(Section 5.1.1.2.)*.

Above all, extreme care should be given to crop establishment and management. In his study on the influences of tillage, Klay (1983) states that "poor and uneven stands is one of the major causes of low crop yields in the semi-arid tropics", while he also refers to severe yield reduction by weeds during the early period of crop growth, caused by competition for water and nutrients. Where growth conditions are improved, these aspects become even more urgent. In that case the use of a uniform bed-and-furrow configuration, together with improved implements seems required, as simpler techniques can hardly guarantee sufficiently good performance.

9.4.3. Execution of Development Plans

As stated before, watershed development in the semi-arid tropics should serve the objectives of both resource protection and increased productivity. Although the latter is not the least important, it should only be aimed at in combination with the former; created increase of production potential should not be endangered by subsequent erosion. Measures concentrating on resource protection only may well be executed as a single (or major) objective. In this case there is almost no question of short term profitability and although the land users should be involved in planning, execution and maintenance, the involved costs should not be passed on to them.

In the other situation, however, the farmers are much more a party in development as they should agree and be able to work in a renewed watershed lay-out, with other techniques and at a higher level of costly inputs. The farmers should be willing and available to provide knowledge, labour, capital and co-operation at the required level. Even if a sufficient availability of inputs is secured from outside and the profitability of the system has been proven, the individual farmer remains with the uncertainty of continuing support from outside and continuing co-operation from within the area. New dependencies may strengthen his doubt.

Development plans, therefore, should first of all be based on ability and willingness to cooperate. Doherty (1982) sets limits to possibilities for "group action" in semi-arid India, both in respect to the number of participants as well as to the duration. Following his line of thought, watershed development plans, if properly sized, could well be organised and executed by groups of farmers in India. For long term management and maintenance, however, other institutions should be created.

To improve the productivity in rainfed agriculture, supported by a renewed system of land- and watermanagement, interventions in existing land properties can not always be avoided. Land consolidation is required or at least very helpful in order to come to an optimal design of surface drainage and the best shapes and sizes of individual fields and the location of reservoirs.

The benefits of watershed development for the individual farmers in rainfed red soil areas are very difficult to estimate. Most construction work involved, apart from that of reservoir construction, relates to watershed protection and can not be considered to yield direct benefits.

An important part of the construction of protection works consist of earthwork. The greater part of this, if not all, can be done with handlabour, as under Indian conditions the labour surplus outside the growing season makes its opportunity cost low. Activities that directly relate to a farmer's own field and its productivity could possibly be done with family labour. In such a situation the construction of small reservoirs, for example, can be cheap and consequently be made profitable.

Sharma *et.al.* (1983) calculated the benefit/cost ratio of small, lined reservoirs in Uttar Pradesh (India) that were recently constructed and still being constructed by individual farmers. Only after exluding the cost of family labour, the ratio came above unity.

The farmer's major expenses comprise the cost of equipment and a much higher level of variable costs for seed and fertilizer. The yield potentials under such a system are also high if sufficient water is available when required. The always present risk of crop-failure, that forces subsistence farmers to low-input systems, should be compensated by an appropriate guarantee, possibly given by a system of rural work programs.

9.5. Concluding Remarks

The ICRISAT-concept of watershed development in order to stimulate productivity of rainfed agriculture in the semi-arid tropics is basically sound. Point-wise it aims at:

- creating an optimal profile condition for crop growth;
- ascertaining accuracy and timeliness in all field operations;
- using crop varieties and cropping systems with a high yield potential, rightly supported by fertilization and crop protection;
- stimulating *in situ* water conservation;
- protecting the area against degradation through erosion;
- collecting excess water for subsequent use.

The translation towards a system of watershed development, based on a bedded field lay-out, the use of a bullock-drawn wheeled tool carrier with attachments and modern varieties appears to combine these aims and to respond well in medium-deep and deep Vertisol areas. Water collection and re-utilization, however, do not seem to be a pertinent profitable technique in view of the already high profile water retention capacity of the Vertisols. Otherwise, this system appears to be able to remove a number of constraints that are met in the traditional system of management and strongly related to surface drainage and timely operations. This even makes it possible to grow a rainy season crop in extended areas that are left fallow during the humid period in more traditional systems.

It has not long been appreciated that the physical constraints of the red soils for an innovative system of production, are different from those of the Vertisols under identical climatic conditions. Red soils are always rainy season cropped and field accessibility is much less of a problem. Loss of water through runoff, however, is a more serious problem as it starts to occur much earlier in the season than from Vertisols. Another problem is the low profile's capacity to store water.

The land management system with the use of a bedded surface configuration might also for red soils be beneficial in respect to quality of field operations, control of excessive runoff and possibility for efficient irrigation. When transferred to the red soils as such, however, it induces runoff in small storm events rather than conserves water as observed in Vertisols.

In red soil areas, with the possible exception of the deep soils, the major constraint relates to timely water availability. A system aiming at a "break-through" in productivity could therefore only be reached if this water is provided.

A large number of questions remain unanswered. Some of them could possibly be attended to in subsequent research. To assess an overall value for the feasibility of the approach as a whole, experimental lay-outs at farmer's level are required for long-term evaluation. Farmers should be given the opportunity to become experienced in working in a renewed system and to develop their own decision criteria for managing the system.

CHAPTER 10 SUMMARY

Rainfed agriculture is defined as the production of field crops that completely depend on the local precipitation for their water supply. Although in the semi-arid tropics the mean annual precipitation might seem to be sufficient to grow (adapted) crops, its variability over the years and its erratic distribution over the season pose problems. During relatively dry periods, the crop might suffer from moisture stress, at other times excessive rainfall occurs, causing water logging and erosion. This creates specific problems for crop production. The red soils, as a general indication of a group of mainly sandy loam soils, including Alfisols, have a low profile water storage capacity, often aggravated by their shallowness. Therefore, they generally lack sufficient buffer capacity to transfer water from a rainy period to a subsequent period of insufficient rainfall. Thereby, red soils have a poorly developed structure and the aggregates of the topsoil are easily dispersed upon wetting, resulting in a surface sealing. Raindrop impact causes a further compaction of the top layer. Under these adverse conditions, the infiltrability of the red soils will be strongly reduced and frequently surface runoff occurs well before the profile is saturated, even early in the rainy season.

Production levels under such water-limited conditions are bound to be low. Yet, millions of people in the semi-arid tropics depend on them. In tropical India alone, the area of red soils that is yearly cropped can be estimated at as much as 50 million hectares. Common food-crops are mostly local varieties of sorghum, millets and grams, with average yield levels well below 1 t/ha. Important cash crops include groundnut, castor and sesame, with similarly low yields. Expansion of agricultural fields, in the case of red soils mainly under the pressure of population growth has been bringing less suitable areas under permanent cultivation and worsening crop rotation over the last 50 years or so. This leads to a further impoverishment of the soils.

Shortage of sufficient water at the right time has always been a problem the farmers in the drier regions of the world have had to face. Depending on the land conditions and climate, different systems have been developed in order to tackle this problem. Some techniques are briefly described (*chapter 4*). Unfortunately, most techniques are based on the availability of a high retention capacity of the profile to store water, which makes such system unsuitable for red soil areas.

In national and international agricultural research, attention is in the first place focussed on the development and introduction of modern crop varieties in combination with the use of synthetic fertilizer. Suitable varieties are the ones that have a higher yield potential and relatively good properties in respect to drought resistance or -avoidance as well as a minimum susceptibility to pests and diseases. Additional attention is given to beneficial crop combinations in respect to efficient water and nutrient use.

More than the traditional cultivars, improved varieties require uniformly good growth conditions for optimal production. Moreover, higher demands are set for accurate and timely soil- and crop management, including seed bed preparation, seeding, fertilizer placement and mechanical weed control. As the technology that is traditional for the rainfed areas of India can not fulfill all these requirements at the proper level, introduction of improved implements and land management appears necessary. In combination with this there is the assumption that observed problems on excessive runoff, local water stagnation and high erosion could be dealt with much better in a bedded field than in the traditionally flat cultivated fields.

At ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Hyderabad, India, these assumptions have lead to the introduction on experimental scale of such field lay-outs together with bullock-drawn wheeled tool carriers. For the sandy Alfisols the system of ridges was abandoned soon after introduction, because they proved unstable and difficult to handle with most field operations. The system of a bed-and-furrow configuration, however, continued to be used and seemed workable in combination with the improved equipment. However, in contrast to its performance on Vertisols, the system when used on the Alfisols appeared to result in higher runoff and soil loss compared to flat cultivated fields.

In this study for which experimental work was done at the ICRISAT research station, a number of observations are reported that helped to validate assumptions on the runoff characteristics of red soils and to understand the reasons for the differences between surface treatments in this respect.

As the infiltrability of red soils is easily reduced to low values through surface sealing, the surface depression storage proves to become an important parameter that influences the cumulative infiltration, as it most effectively prolonges the time of residence of the water in the field and therewith the time available for infiltration.

Micro-depression storage (or surface retention) is related to the surface roughness and can be appreciable directly after cultivation. Under the influence of (heavy) rain , however, a rapid and almost complete decline of it can be observed *(section 6.1.1.2)*, mainly due to the low stability of the top soil. Only shallow depressions will be left, which on top of a more or less crowned shaped bed have little or no storage capacity, while they do have at least some in a flat cultivated field.
Mini-depressions, as formed by unintended marks and irregularities, are much more stable but have a low storage capacity. Mini-depressions could also be created purposely, for example by damming furrows at intervals, which is only feasible on bedded fields. Under the conditions of Hyderabad, they do not prove effective.
Macro-depressions, as far as they are formed by topografic undulations within the field, also pose a difference between flat cultivated and bedded fields, as in the latter the stagnation of the water is restricted to the furrows. This can be a major advantage of the use of beds, as prolonged stagnation of water, resulting from continuing rain, will adversely affect most crops in the waterlogged areas.
Mainly by the differences in depression storage between flat and bedded fields, their runoff performance is also different; actual differences thereby depend on size and intensity of individual storms *(section 6.2.2.)*.

At the same time, approaches to reduce runoff and erosion from bedded fields were searched for. In this respect a much more intense system of primary tillage, as compared to the usual way of ploughing beds at ICRISAT, earlier proposed by Klay (1983) proved to increase infiltration *(section 6.1.1.)*. A significant difference in bulk density of the top soil was measured even by the end of the growing season.
The influence of the shape of the bed-and-furrow on runoff behaviour was observed and hydraulic roughness co-efficients of the furrows calculated *(section 6.2.3.)*. Again, as with the difference between flat and bedded fields, the pros and cons of a certain shape and size of the furrow also depend on the expected storm sizes. For Hyderabad, however, preference goes to narrow furrows along with a level bed. This is also the shape that is easiest to handle with bullock-drawn implements.

Observation on erosion and soil loss *(chapter 7)* stressed the need to differentiate between the local loss of soil within a field and the ultimate sediment yield at a measuring point. The necessity to include the composition of transported material in comparison to that of *in situ* material is made clear and its difference expressed as "dispersion co-efficient". Measurements on the texture of eroded material over the season, showed the occasionally high values of this dispersion co-efficient. The high contribution of suspended material, particularly for red soils, in total soil-loss was obvious from the experiments.

Although a more intense system of tillage, both in respect to depth and frequency, might well be able to decrease runoff, the maximum storage capacity of red soil profiles may often become a limiting factor. Most red soils have a profile retention capacity below 150 mm of crop available water, frequently even below 100 mm. In many years, this will prove to be too low a reserve to adequately support a standing crop during the droughty periods that can be expected to occur in the semi-arid tropics. Observations at ICRISAT are referred to *(section 8.3.)*, where small amounts of water, applied as supplementary irrigation during periods of stress, resulted in considerable yield increases. But small water gifts that supported the growth of an additional post-rainy season crop also proved to be very effective. As far as no other source of water is available but the local precipitation, water for supplementary irrigation has to be drawn from earlier rainfall excess that has lead to surface runoff and has been collected in (excavated) reservoirs. Chapter 8 describes two alternatives for such an approach. Firstly, a runoff collection and water re-utilization system could be based on the collection of all season's expected runoff leaving the choice open, depending on the season, to use this water to break dry spells or to support a subsequent crop, possibly on a reduced area. Such a system would be based on reservoirs, with a storage capacity of say 5,000 - 6,000 m^3 for a 5 ha area (100 - 120 mm on area basis). The second system would be based on a field-scale water collection. Here, the envisaged storage capacity would amount to a much lower value of, say, 40 mm on area basis, or 200 m^3 for a 0.5 ha field. In this latter approach collected runoff mainly serves as a source for supplementary irrigation during dry spells.

A choice between the two systems is complicated and, among others, depends on local precipitation, soil depth, grown or envisaged crops and available technology. Yet, a number of small reservoirs might well have some distinct advantages over a single larger one. These relate to a higher water collection efficiency, increasing the probability of a filled reservoir at the time the water is needed and to the possibility for small farm units

(0.5 ha) to use the water at the right moment, using simple (and cheap) means for water lifting and transport. The relatively higher seepage from small reservoirs, c.q. the relatively higher costs for lining them, might be made good by a higher frequency of use, as the reservoir will mostly be filled up again after water extraction.

In watershed development in red soil areas in the semi-arid tropics attention is generally directed to both resource protection and increase of productivity. Only the former could possibly be considered as a single objective. In the combined objective, the land users have to drasticly change their systems of farming, as traditional technology already uses the environment to its optimum. Introduction of modern crop varieties and fertilization, costly inputs, should go along with an optimum management of the land, the soil and the water. Watershed development in this context is only possible if farmers are able and willing to spend knowledge, labour, capital and co-operation at the required level.

For reaching this goal, relevant groups of farmers should be organised to enable co-operation in necessary land consolidation and construction work. For longer term maintenance work and for the organisation of machine pooling etc., separate bodies are required.

CHAPTER 11 SAMENVATTING

Regenafhankelijke landbouw is gedefinieerd als de produktie van gewassen die voor hun watervoorziening volledig afhankelijk zijn van de lokale neerslag. Hoewel de gemiddelde jaarneerslag in de semi-aride tropen voldoende hoog lijkt te zijn voor de verbouw van een (aangepast) gewas, geeft de variatie ervan over de jaren en de onregelmatige verdeling binnen het seizoen aanleiding tot problemen. Een gewas kan schade ondervinden door vochttekort door relatief droge perioden terwijl op een ander moment overvloedige regenval optreedt met stagnerend water en erosie als gevolg. Dit veroorzaakt specifieke problemen voor gewasproduktie. De rode gronden, als een algemene aanduiding van een groep voornamelijk zanderige leemgronden, waaronder Alfisolen, hebben een laag vochtvasthoudend vermogen, versterkt door hun vaak ondiepe profielen. Daarom missen ze over het algemeen voldoende buffercapaciteit om water over te dragen van een natte periode naar een opvolgende periode met onvoldoende neerslag. Daarbij komt dat de rode gronden een slecht ontwikkelde structuur hebben en dat de aan de oppervlakte blootgestelde aggregaten makkelijk uiteen vallen bij bevochtiging, resulterend in de vorming van een korst. De inslag van regendruppels veroorzaakt een verdere verdichting. Onder deze ongunstige omstandigheden wordt de infiltratiesnelheid van de rode gronden sterk verlaagd met als gevolg dat vaak oppervlakkige afstroming plaatsvindt zonder dat het profiel verzadigd is, zelfs vroeg in het regenseizoen.

Onder dergelijke omstandigheden van beperkte beschikbaarheid van water zijn de opbrengsten logischerwijs laag. Toch zijn miljoenen mensen in de semiaride tropen ervan afhankelijk. Alleen al in tropisch India, kan het areaal aan rode gronden dat jaarlijks verbouwd wordt geschat worden op niet minder dan 50 miljoen hectare. Gebruikelijke voedselgewassen zijn over het algemeen de lokale variëteiten van sorghum, giersten en peulvruchten, met gemiddelde opbrengsten ver onder de 1 t/ha. Belangrijke handelsgewassen worden gevormd door aardnoot, castor en sesam, met eveneens lage opbrengsten. Uitbreiding van het landbouw-areaal, wat de rode gronden aangaat vooral onder de druk van bevolkingsgroei, heeft gedurende ruwweg de laatste 50 jaar geleid tot ingebruikname van minder geschikte gebieden voor permanente akkerbouw en heeft de kwaliteit van de gewasrotatie verslechterd. Dit leidt tot een verdere verarming van de bodems.

Gebrek aan voldoende water op het juiste moment is een probleem waarmee de boeren in de drogere gebieden van de wereld altijd al geconfronteerd zijn geweest. Afhankelijk van terreinomstandigheden en klimaat, zijn verschillende systemen ontwikkeld om dit probleem te ondervangen. Enkele technieken worden in het kort beschreven (<u>Hoofdstuk 4</u>). Ongelukkigerwijs zijn de meeste technieken gebaseerd op de beschikbaarheid van een hoog water vasthoudend vermogen van het profiel om water op te slaan, waardoor zulke systemen ongeschikt zijn voor gebieden met rode gronden.

In nationaal en internationaal landbouwkundig onderzoek is de aandacht op de eerste plaats gericht op het ontwikkelen en introduceren van moderne gewasvariëteiten gecombineerd met het gebruik van kunstmest. Geschikte variëteiten hebben een hogere opbrengstpotentie en relatief goede eigenschappen op het gebied van droogtetolerantie of -vermijding, met daarbij een minimale vatbaarheid voor plagen en ziektes. Daarnaast wordt aandacht gericht op gunstige gewascombinaties voor een efficiënt gebruik van water en voedingsstoffen.

Meer dan de traditionele cultivars, vereisen verbeterde variëteiten uniform goede groeiomstandigheden voor optimale produktie. Bovendien worden er hogere eisen gesteld aan een nauwkeurige en bijtijdse verzorging van bodem en gewas, zoals bij zaaibedbereiding, zaaien, toedienen van kunstmest en mechanische onkruidbestrijding. Omdat de technologie die traditioneel is voor de regenafhankelijke landbouwgebieden in India niet voldoende aan al deze behoeftes tegemoet kan komen, blijkt de introductie van verbeterde werktuigen en veldinrichting noodzakelijk te zijn. Gecombineerd hiermee wordt aangenomen dat waargenomen problemen van buitensporige afstroming, lokale waterstagnatie en hoge erosie veel beter aangepakt kunnen worden in een veldinrichting met bedden en voren dan in de traditioneel vlak gecultiveerde velden.

Bij ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Hyderabad, India, hebben deze aannames geleid tot de invoering op experimentele schaal van een dergelijke veldinrichting, samen met een door twee trekdieren voortbewogen werktuigraam. Voor de zanderige Alfisolen werd het systeem van smalle ruggen alweer snel verlaten, omdat de ruggen instabiel bleken te zijn en moeilijk te bewerken bij de meeste operaties. Het systeem van bedden bleef echter in gebruik en leek bruikbaar in combinatie met de verbeterde werktuigen. Echter, in tegenstelling tot gebruik op Vertisolen, bleek dit systeem op Alfisolen te resulteren in een verhoogde afstroming en bodemverlies in vergelijking tot vlak gecultiveerde velden.

In deze studie, waarvoor experimenten werden gedaan op het onderzoeksstation van ICRISAT, worden een aantal waarnemingen gerapporteerd die hebben geholpen om aannames aangaande afstromingskarakteristieken van rode gronden op hun waarde te taxeren, en om in dit verband de oorzaken te begrijpen voor de verschillen tussen oppervlaktebehandelingen.

Omdat de infiltratie van rode gronden snel en sterk achteruit gaat door de vorming van een korst, blijkt de oppervlakkige berging in depressies een belangrijke parameter te worden die de cumulatieve infiltratie bepaalt, omdat deze op de meest effectieve wijze de verblijfstijd van het water in het veld verlengt en daarmee de tijd beschikbaar voor infiltratie.

De berging in micro-depressies (of oppervlakteretentie) is gerelateerd aan de oppervlakteruwheid en kan aanzienlijk zijn direct na een bewerking. Onder invloed van (zware) regen, kan echter een snelle en bijna volledige afname ervan waargenomen worden (paragraaf 6.1.1.2), vooral vanwege de lage stabiliteit van de bovengrond. Alleen ondiepe depressies zullen overblijven, die op een min of meer afgerond bed weinig of geen bergingscapaciteit hebben, terwijl ze in een vlak gecultiveerd veld tenminste enige berging hebben.
Mini-depressies, voorzover gevormd door toevallige afdrukken en onregelmatigheden, zijn veel stabieler, maar hebben een lage bergingscapaciteit. Mini-depressies kunnen ook opzettelijk gecreëerd worden, bijvoorbeeld door voren op regelmatige afstanden af te sluiten, wat alleen relevant is in velden met bedden. Onder de omstandigheden van Hyderabad blijken zij niet effectief te zijn.
Macro-depressies, voorzover zij worden gevormd door topografische hoogteverschillen binnen het veld, geven ook aanleiding tot een verschil tussen vlak bewerkte velden en velden met bedden, omdat in het laatste geval de stagnatie van het water beperkt is tot de voren. Dit kan een belangrijk voordeel zijn van het gebruik van bedden, omdat langdurige waterstagnatie op die plekken, als gevolg van aanhoudende regen, de meeste gewassen nadelig zal beïnvloeden.
Vooral door de verschillen in berging in depressies tussen vlak bewerkte velden en velden met bedden, is hun afstroming ook verschillend; feitelijke verschillen zijn daarbij afhankelijk van grootte en intensiteit van individuele regenbuien (paragraaf 6.2.2.).

Gelijktijdig is er gezocht naar benaderingen die de afstroming en erosie van het beddensysteem konden verminderen. Wat dit betreft, bleek een systeem van primaire grondbewerking dat veel intensiever is in vergelijking tot de op ICRISAT gebruikelijke manier van het ploegen van de bedden, eerder voorgesteld door Klay (1983), de infiltratie te verhogen (paragraaf 6.1.1.). Zelfs tegen het eind van het groeiseizoen werd een significant verschil in dichtheid van de bovengrond gemeten.
De invloed van de vorm van het bed en de vore op de afstroming werd geobserveerd en coëfficiënten voor de hydraulische ruwheid berekend (paragraaf 6.2.3.). Net als bij het verschil tussen vlakke velden en velden in bedden, hangen de vóór- en nadelen van een bepaalde vorm en afmeting van de vore ook weer af van de te verwachten bui-groottes. Voor Hyderabad gaat de voorkeur echter naar nauwe voren samen met een vlak bed. Dit geeft ook de vorm die het eenvoudigste te behandelen is met werktuigen met ossentractie.

Waarnemingen op het gebied van erosie en bodemverlies (hoofdstuk 7) benadrukten de noodzaak om een onderscheid te maken tussen het lokale bodemverlies binnen een veld en de uiteindelijke sediment-opbrengst bij een meetpunt. De noodzaak om de samenstelling van getransporteerd materiaal te includeren in vergelijking tot dat van het *in situ* materiaal wordt duidelijk gemaakt en het verschil uitgedrukt als 'dispersie-coëfficiënt'. Bepaling van de textuur van geërodeerd materiaal over het seizoen, toonde de soms hoge waardes van deze dispersie-coëfficiënt. De hoge bijdrage van materiaal in suspensie, in het bijzonder voor rode gronden, aan het totale bodemverlies, kwam bij de experimenten duidelijk naar voren.

Hoewel een intensiever bewerkingssysteem, zowel wat diepte als wat frequentie aangaat, in staat zal kunnen zijn om afstroming te verlagen, kan de bergingscapaciteit van de rode gronden vaak een beperkende factor worden.
De meeste rode gronden hebben een bergingscapaciteit voor gewas beschikbaar bodemvocht kleiner dan 150 mm, vaak zelfs minder dan 100 mm. In vele jaren zal dit een geringe reserve blijken te zijn om een gewas adequaat te ondersteunen gedurende de periodes van onvoldoende neerslag, zoals die in de semi-aride tropen verwacht kunnen worden. Er wordt verwezen naar waarnemingen bij ICRISAT (paragraaf 8.3), waar kleine hoeveelheden water, toegediend als supplementaire irrigatie gedurende periodes van watertekort, resulteerden in aanzienlijke opbrengststijgingen. Maar ook kleine watergiften ter ondersteuning van de groei van een additioneel gewas, aansluitend aan de regentijd, bewezen zeer effectief te zijn. Voorzover er geen andere bron voor water aanwezig is dan de lokale regenval, moet water voor supplementaire irrigatie geput worden uit eerder opgetreden overschotten van regen, die hebben geleid tot oppervlakkige afstroming en wat verzameld is in

(gegraven) reservoirs. Hoofdstuk 8 beschrijft twee alternatieven van deze benadering. Als eerste kan een systeem van wateropslag en hergebruik gebaseerd zijn op het verzamelen van de totale hoeveelheid te verwachten afstroming gedurende het regenseizoen. Het gebruik van dit water ligt niet vast en kan, afhankelijk van het seizoen, aangewend worden om droogteperiodes te doorbreken of om een volgend gewas te ondersteunen, mogelijkerwijs op een beperkt oppervlak. Een dergelijk systeem zou gebaseerd zijn op reservoirs met een opslagcapaciteit van zeg 5.000 - 6.000 m^3 voor een gebied van 5 ha (100 - 120 mm op oppervlaktebasis). Een tweede mogelijk systeem zou gebaseerd zijn op wateropvang op veldniveau. In dit geval, zou de te voorziene opslagcapaciteit veel lager liggen, misschien 40 mm op gebiedsbasis, oftewel 200 m^3 voor een veld van 0.5 ha. Bij deze laatste benadering dient het opgevangen water vooral als bron voor supplementaire irrigatie gedurende droogte-intervallen.

Een keuze tussen de twee systemen is gecompliceerd en hangt onder andere af van de lokale neerslag, bodemdiepte, verbouwde of voorziene gewassen en beschikbare technologie. Toch zou een aantal kleine reservoirs enige duidelijke voordelen kunnen hebben boven een enkel groter reservoir. Deze voordelen zijn gerelateerd aan een hogere efficiëntie van wateropvang, waarmee de waarschijnlijkheid vergroot wordt dat het reservoir gevuld is op het tijdstip dat er water nodig is en aan de mogelijkheid voor kleine landbouweenheden (0,5 ha) om het water op het juiste moment te gebruiken met behulp van eenvoudige (en goedkope) middelen van wateropvoer en transport. De relatief hogere percolatie van kleine reservoirs, c.q. de relatief hogere kosten voor bekleding van de reservoirs, zouden gecompenseerd kunnen worden door een hogere frequentie van gebruik, gezien het feit dat het reservoir meestal weer opgevuld zal raken na eerdere wateronttrekking.

Bij de ontwikkeling van vanggebieden in regio's met rode gronden in de semi-aride tropen is de aandacht over het algemeen gericht op zowel bescherming van het gebied als op een verhoging van de produktiviteit. Alleen de eerste doelstelling zou mogelijkerwijs als losstaand doel beschouwd kunnen worden. In de gecombineerde benadering moeten de landgebruikers hun systeem van landbouw drastisch veranderen, omdat de traditionele technologie de omgeving al optimaal gebruikt. Introductie van moderne gewasvariëteiten en bemesting, dure inputs, moet samengaan met een optimaal gebruik van het land, de bodem en het water. In deze context is de ontwikkeling van een vanggebied alleen maar mogelijk als de boeren in staat zijn om kennis, arbeid, kapitaal en samenwerking te besteden op het benodigde niveau.

Om dit doel te bereiken, moeten relevante groepen van boeren georganiseerd worden om samenwerking voor de noodzakelijke landverkaveling en constructiewerk mogelijk te maken. Voor onderhoudswerk op de langere termijn en voor de organisatie van het gezamenlijk gebruik van werktuigen, enz., zijn afzonderlijke organisatiestructuren nodig.

APPENDIX 1

Profile Description of Typical Shallow and Medium Deep Alfisol

(a) Shallow. (Location: ICRISAT, RA-18, Patancheru, A.P. India)

Horizon	Depth (cm)	Description
A_p	0-15	Reddish brown (5YR 6/4 dry); yellowish red (5YR 4/6 moist); coarse sandy loam; single grain with few medium very weak, subangular blocky peds; dry loose, moist very friable; few fine inped roots; few fine pores in undisturbed peds; clear smooth boundary.
BC	15-26,5	(Stoney) gravelly sandy clay loam with common medium to coarse iron concretions; dry hard, moist friable; few fine exped roots; abrupt smooth boundary.
R	26,5 +	Parent Rock.

Drainage and Permeability: Moderately rapid with moderate permeability.
Placement - Fine loamy hyperthermic family of Ustochrept.

(b) Medium Deep. (Location: ICRISAT, RC-1, Patancheru, A.P. India)

Horizon	Depth (cm)	Description
A_p	0-18,5	Yellowish red (5YR 5/6 dry); yellowish red (5YR 4/6 moist); sandy clay loam; medium weak granular to single grain; dry loose, moist friable; few fine roots; pH 6.7.; gradual smooth boundary.
B 2	18,5-35	Dark red (2,5 YR 3/6 dry); dark reddish brown (2,5 YR 3/4 moist); clay; medium moderate subangular blocky; dry semi-hard, moist friable, wet sticky and plastic; few fine irregular open pores; few fine roots; pH 5.8.; gradual smooth boundary.
B_{21t}	35-62,5	Dark reddish brown (2,5 YR 3/4 dry and moist); clay; moderate medium subangular blocky; dry hard, moist firm, wet sticky and plastic; few fine irregular open pores; very few fine roots; pH 6.1.; gradual smooth boundary.
B_{22t}	62,5-105	Dark red (2,5 YR 3/6 dry); dark reddish brown (2,5 YR 3/4 moist); clay with many fine iron concretions; few irregular pores; few thin patchy clay skins; pH 6.4.; gradual and smooth boundary.
B_3	105-145,5	Dark red (2,5 YR 3/6 dry); dark reddish brown (2,5 YR 3/4 moist); gravelly clay; medium moderate subangular blocky; dry loose, moist friable, wet slightly sticky; few fine iron concretions; pH 6.6.; many silica gravel pieces.

Drainage and Permeability: Moderately well drained with moderately slow permeability.
Placement - Fine, hyperthermic family of Typic Paleustalf

Source: Singh and Krantz (1976)

APPENDIX 2
Calculation Procedure of Profile Water Lines

To arrive at the profile water lines as depicted in figures 4.1. through to 4.3., section 4.5., a calculation procedure was used, based on actual precipitation and measured runoff values, supplemented with assumed values for evaporation and transpiration. A computer programme was developed to calculate daily values of the storage component, STOR(I), which were afterwards substituted in 3-day moving averages, as shown in the figures.

For the calculation, a period of 120 days, starting June 1st, was divided into five intervals, related to date of sowing (NZ) *(table A.1.)*. To each period a value for potential evaporation (E_o) and potential transpiration (T_o) was assigned. Actual evaporation (E_a) was assumed to be about half the potential rate in the situation of consecutive wet days, as such a period is characterised by a higher level of cloudiness, lower temperature and higher air humidity. Otherwise, the actual daily evaporation rate was calculated according to the formula:

$$E_a = E_o/N \quad \text{(mm/day)} \qquad \text{(A.1.)}$$

with N the number of days since last rainfall *(section 5.3.2.)*. Cumulative evaporation for consecutive dry days, however, was not allowed to exceed the amount of precipitation of the previous storm.

Transpiration was assumed to be at the potential level ($T_a = T_o$) as long as sufficient profile storage was available. Available moisture in deeper profiles will generally be distributed over more depth than in more shallow profiles. Consequently, the profile moisture content at which the availability of water starts to be restrictive for optimal crop transpiration will be higher for deeper profiles. Dependent on this profile storage capacity, a threshold value for freely available water was fixed at the value: 0.25 PS + 20 (mm), with PS as the assumed profile storage (mm), available for transpiration. When, after crop establishment, the actual profile storage came below this value, actual transpiration was assumed to stay behind the potential rate, according:

$$T_a = f \times T_o \, , \qquad \text{(A.2.)}$$

$$\text{with} \quad f = \frac{\text{STOR (I)}}{0.25 \times \text{PS} + 20} \qquad \text{(A.3.)}$$

Table A.1. Values for evaporation and transpiration used in water balance calculation

interval+)	E_o	E_a x)	T_o
	(mm/day)	(mm/day)	(mm/day)
< NZ	10	5	-
NZ - NZ+21	5	3	1
NZ+21 - NZ+42	5	2	3
NZ+42 - NZ+70	3	2	5
> NZ+70	3	2	3

+) NZ : date of sowing
x) in the case of consecutive wet days

The time intervals where this transpiration reduction occurred, are indicated in the figures. Further depletion of the profile moisture leads to the point of severe crop water stress, which always has a distinct yield reducing effect. In this calculation, this point was assumed to be reached when actual transpiration became half the potential rates or lower. Such periods are also indicated in the figures.

The calculated lines are clearly rough approximations of reality, but do indicate important trends. Their applicability is restricted to red soils.

APPENDIX 3

Frequency of Occurrence of Different Storm Sizes in Weekly Periods (Hyderabad, India: 1901 - 1970)

Week from		Storm size intervals (mm)								
		5-10	10-15	15-20	20-30	30-40	40-50	50-60	60-80	> 80
April	2	5	4	2	4	1	0	0	0	0
	9	8	3	4	4	2	1	0	0	0
	16	12	6	0	3	2	0	0	1	0
	23	12	4	1	3	2	1	0	0	0
	30	9	5	2	2	1	0	1	0	0
May	7	9	0	2	3	0	0	0	0	0
	14	9	4	1	3	3	0	0	1	0
	21	16	10	10	6	1	2	1	0	0
	28	18	8	4	5	2	0	0	0	0
June	4	21	8	10	5	4	4	2	1	0
	11	28	12	9	8	3	2	1	2	1
	18	31	20	11	20	4	6	4	0	2
	25	43	19	17	19	10	8	3	1	1
July	2	40	20	16	20	6	4	3	1	1
	9	47	24	13	13	8	6	0	2	2
	16	51	27	20	21	13	7	2	3	0
	23	44	39	17	20	13	8	5	2	0
	30	54	26	22	20	7	3	5	0	1
Aug.	6	37	20	14	11	5	4	2	1	1
	13	43	21	18	15	7	4	2	1	0
	20	32	28	8	23	6	2	2	6	2
	27	37	26	13	19	7	7	3	1	2
Sept.	3	46	18	14	18	10	9	3	2	3
	10	37	24	15	16	11	4	5	8	1
	17	51	22	12	17	11	9	6	2	2
	24	35	15	18	12	12	6	2	2	5
Oct.	1	27	6	9	8	4	1	0	3	2
	8	16	19	9	5	5	4	1	1	0
	15	14	11	9	8	5	1	4	2	0
	22	17	7	3	10	3	1	0	3	1
	29	9	10	4	7	2	1	0	2	2
Nov.	5	11	13	3	6	1	0	0	0	0
	12	4	6	2	0	1	0	1	1	0
	19	7	1	1	2	0	1	0	2	0

APPENDIX 4

Infiltration Measurements Using 15 cm Single Rings

Values shown were obtained after correction for lateral flow *(see text, section 5.3.1. Equation. 5.7.)*

(a) Bedded Field (RW-3F, plot 7)

Time elapsed (min.)	Corrected Infiltration Rates (cm/h)							
	Cultivated zone				Traffic zone			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
2.5	39.2	42.3	34.8	44.4	-	-	-	-
7.5	11.7	15.8	11.3	18.0	-	9.4	10.1	-
15	6.8	9.3	7.0	10.8	4.1	5.3	6.3	4.8
25	4.3	6.5	4.8	7.7	2.8	3.7	4.3	3.2
45	2.8	4.2	2.8	4.6	1.8	2.4	2.7	2.0
90	1.7	2.6	1.6	2.8	1.0	1.4	1.5	1.1
150	1.2	1.8	1.1	1.9	0.7	1.0	1.1	0.8
210	0.9	1.4	0.9	1.4	0.5	0.8	0.9	0.6
270	0.8	1.2	0.8	1.2	0.4	0.6	0.7	0.5

(b) Flat Cultivated Field (RW-3F, plot 5)

Time elapsed (min.)	Corrected Infiltration Rates (cm/h)									
	Cultivated zone					Traffic zone				
	(5)	(6)	(7)	(8)	(9)	(5)	(6)	(7)	(8)	(9)
2.5	47.8	41.4	42.5	36.3	44.0	-	-	-	-	-
7.5	15.2	17.2	15.4	15.8	17.2	-	10.8	11.7	10.4	10.1
15	9.2	10.4	9.6	10.0	11.6	4.7	6.5	6.7	6.1	6.7
25	6.3	7.2	6.5	7.2	8.1	3.2	4.1	4.4	4.0	4.3
45	3.9	4.9	3.9	4.8	5.3	2.0	2.7	2.8	2.5	3.0
90	2.3	3.0	2.4	3.1	3.3	1.1	1.6	1.6	1.6	2.0
150	1.6	2.1	1.6	2.2	2.3	0.8	1.1	1.1	1.1	1.4
210	1.3	1.6	1.2	1.7	1.8	0.6	0.9	0.8	0.9	1.1
270	1.1	1.3	1.0	1.5	1.5	0.5	0.8	0.7	0.8	1.0

(c) The measured infiltration rates can be described well by the formula proposed by Kostiakov (1932):

$$I_{cum} = A \cdot t^{B} \qquad \text{(A.4.)}$$

with:

I_{cum} = cumulated infiltration at time t (mm);

t = infiltration time (min.);

A = cumulative infiltration at $t = 1$;

B = dimensionless exponent.

The infiltration measurements shown in figure 5.7. of section 5.3.1. can consequently be described as:

$$I_{cum} = 7.9 \times t^{0.52} \quad (r = 0.99) \qquad (A.4.(a))$$
$$I_{cum} = 20.6 \times t^{0.33} \quad (r = 0.99) \qquad (A.4.(b))$$
$$I_{cum} = 20.3 \times t^{0.36} \quad (r = 0.99) \qquad (A.4.(c))$$

The infiltration curves also obey the equation proposed by Philip (1957):

$$I_{cum} = S \cdot t^{\frac{1}{2}} + A \cdot t \qquad (A.5.)$$

with:

I_{cum} = cumulative infiltration at time t (cm);
S = sorptivity ($cm.sec^{-1}$);
t = time (sec);
A = constant.

and can be described as:

$$I_{cum} = 0.1244 \cdot t^{\frac{1}{2}} - 0.00014 \cdot t \quad (r = 0.97) \qquad (A.5.(a))$$
$$I_{cum} = 0.2049 \cdot t^{\frac{1}{2}} - 0.0007 \cdot t \quad (r = 0.98) \qquad (A.5.(b))$$
$$I_{cum} = 0.1936 \cdot t^{\frac{1}{2}} - 0.0008 \cdot t \quad (r = 0.96) \qquad (A.5.(c))$$

APPENDIX 5

The Measurement of Surface Roughness

The value for the random roughness is based on height measurements of a large number of points in a grid. For this purpose a micro-relief meter is used. In its simplest form it consists of a support frame in a fixed position and a line of measuring pins. The latter can move horizontally over the support frame. At each setting one line of heights can be measured with the pins resting on the soil surface and the top of the pins indicating the heights. After a line of measurements, the pins are lifted and shifted to a next position.

Many relief-meters cover an area of 1 m^2, build-up of 20 lines or positions, each line measuring 20 points of elevation. In this way 400 measurements are done in the usual 5 x 5 cm grid (Burwell *et.al.*, 1963; Allmaras *et.al.*, 1966, Moore and Larson, 1979). Monteith (1974) used a grid of 2,5 cm. Mitchell and Jones (1976) also recommend this denser grid on the basis of their analysis of models to quantify the depression storage through micro-relief measurements.

Different calculation methods are used to convert the point measurements into a roughness index. Kuipers (1957) defined the random roughness index (RRI) as

$$RRI = 100 \log s \qquad (A.6.)$$

with s = standard deviation of the measured heights in cm.

Burwell *et.al.* (1963) assumed a log normal distribution of the heights and defined the random roughness index as the standard deviation of their logarithms. Differences between the computation methods, however, prove to be small (Dexter, 1977; Linder, 1979). Preference goes to the simple technique of defining the random roughness as the standard deviation of the measured heights, without log transformation.

To remove the oriented roughness, the standard deviation of the height measurements of individual lines, in the direction of tillage, is calculated, after correction for the general slope (Allmaras *et.al.*, 1966). The mean standard deviation of all lines is then defined as the random roughness.

APPENDIX 6

The Calculation of Surface Storage

Mitchell and Jones (1976) investigated five methods of computing storage from point measurement data. They compared these computation methods with water displacement measurements of artificial surfaces and concluded that most methods give an adequate outcome. The simplest computation method, therefore, is recommended and used by them in further experiments. This method, for a surface in level condition and for point-measurements in a 1-inch grid, may be represented by:

$$S_r = \sum_{i=1}^{m} \sum_{j=1}^{n} (H_r - H_a) \qquad \text{(A.7.)}$$

with:

S_r = accumulated surface storage below a reference height (inches ^{3}).

i,j = rows and columns of point measurements.

H_r = reference height (inches).

H_a = point measurements of height on soil surface (inches).

and: $H_r > H_a$.

Subsequently, out of 15 depth-storage models considered and compared on the basis of accuracy and practicality of use, they selected the relation:

$$S = a \cdot D^b \qquad \text{(A.8.)}$$

with:

S = storage (inches).

D = depth above the lowest point on the surface (inches).

a,b = equation parameters.

The parameters are described in a number of prediction equations, related to relief and soil characteristics on the basis of laboratory- and field-studies.

Moore *et.al.* (1980) modelled surface storage and runoff from small experimental plots based on the direction of flow from individual grid-points and storage in individual depressions. They followed the sequence of events as identified by Linsley *et.al.* *(see section 5.4.)* and the flow approach as used by Seginer (1971). Comparing measurements before and after a simulated rain revealed a 40 to 45% decrease in surface storage caused by the rain. Ploughing increased the maximum storage from 3.2 mm to 11.2 mm on average.

They also found maximum micro-relief storage after rainfall (S_{mp}) and that before rainfall (S_m) to be related, according:

$$S_{mp} = -0.523 + 0.627\ S_m \qquad (A.9.)$$

This equation explained 77 percent of the variance and is significant at the 1 percent level.

APPENDIX 7

The Animal-Drawn Wheeled Tool Carrier

An improved system of farming often requires more timely, more precise and sometimes new types of field operations compared to traditional systems. Often this can not be accomplished with the traditional implements. Particularly in a field lay-out with a bed-and-furrow configuration *(chapter 6)* the use of a "wheeled tool carrier" is inevitable for proper cultivation. "A wheeled tool carrier consists of a frame mounted on two wheels with a beam or drawpole to which a bullock yoke is fastened. The basic frame has a toolbar onto which a variety of implements can be attached with simple clamps. The working depth can be adjusted to meet operational requirements. A mechanical lifting mechanism is provided to raise the implement into a transport position and lower it into the working position" (ICRISAT, 1981).

At ICRISAT's research station the animal-drawn tool carriers have been succesfully used for conducting all operations of tillage, planting and interrow cultivation on up to 60 ha Vertisols and 30 ha of Alfisols for the last ten years or so, as well as for land smoothing and drainage-way construction (Kampen, 1980) *(Figure A.1.)*.
The characteristics of the use of such equipment, on Alfisols, along with a permanent bed-and-furrow system, are related to a much faster ploughing operation, that can be restricted to the cropped zone; a deeper ploughing through an easier running of the equipment; an accurate placement of seed in both vertical and horizontal direction, several rows at a time; an

Figure A.1. A bullock-drawn wheeled tool carrier, making 1,50 m wide beds accurate and fast inter-row weed control and secondary cultivation. Such characteristics could be beneficial or even a prerequisite in systems of farming that include the use of improved varieties and fertilization.

The major drawback for small farmers is the high cost of the equipment. Even a simple wheeled tool carrier, along with basis implements would cost as much as Rs 7000/- (Bansal and Thierstein, 1982). Supposingly, such a set would be capable to cultivate an area of 14 ha per year, and to provide transport in addition to field operations. Bansal and Thierstein derive the cost with such combined use at Rs 150/-[+)] per hectare per year.

It is much more difficult to indicate the economic benefits of the use of such improved equipment. But introduction of it would never be economical if it did not go along with the use of other new inputs, that distinctly increase the production levels. Moreover, ultimate costs will depend on the intensity of use, a factor that is also determined by the way a co-operative use by a group of farmers can be organised.

+) Rs 10/- = 1 US$

APPENDIX 8

Observations on the Effects of Two Methods for Primary Tillage

To enable these observations, two adjacent plots of 6 x 80 meters, located in the area marked RW-3C, were tilled according to a zonal and intensive system respectively (systems 1 and 2, *see text, section 6.1.1.1.*). All beds had been cropped for two previous years and had the same management history. Apart from the system of primary tillage, all other factors were kept the same for both plots. Runoff was measured with a "½.90°" V-notch weir (Bos, 1976) with automatic water level recorder, and a raingauge was placed within the experimental area.

Table A.3. gives observations on the rainfall and runoff for the two treatments, indicating a distinct reduction in runoff after intensive tillage. Table A.4. gives some comparative data on bulk density, plant height and grain yield, which figures are all in favour of the intensive tillage-system.

Table A.3. Effect of intensity of primary tillage on infiltration and runoff

Date	Rainfall	Runoff	
		System 1+)	System 2+)
	(mm)	(mm)	(mm)
30-07-80	23.6	1.2	1.1
14-08-80	16.4	3.1	2.2
19-08-80	114.8	27.4	22.1
20-08-80	72.6	21.8	17.2
03-09-80	22.5	1.5	1.4
06-09-80	31.1	5.2	4.4
24-09-80	14.7	0.3	0.3
Total	295.7	60.5	48.7

+) For explanation see text, section 6.1.1.1.

Table A.4. Summary of observations on bulk density, plant height and grain yield for two differently tilled soils

	dry bulk density	plant height	grain yield
	$(g.cm^{-3})$	(cm)	$(kg.ha^{-1})$
date	19-09-80	27-08-80	14-10-80
System 1	1.55	133.5	1500
System 2	1.48	142.2	1840
S.E.	± 0.019	± 0.018	± 79
C.V. (%)	4	5	17

APPENDIX 9

Influence of Surface Configuration on Runoff and Soil Loss. Small plot Experiments

During the 1980 rainy season runoff and soil-loss were measured from 10 x 4.5 meters plots. 20 Of such plots were located in the RW-3F -area at ICRISAT-station. The surface slope in longitudinal direction was 0.4% and for each plot total runoff per storm could be measured by partial collection of the water in buried drums. First, the runoff water passed through a silt-trap, provided with five outlet tubes, one of which was connected to a drum with a free storage of about 180 liters. The outflow of the tubes was calibrated at different discharges. This set-up allowed the measurement of runoff quantities up to 20 mm per event, after which the drum had to be emptied again.

The experiment was designed to compare runoff and soil loss from plots with a different surface configuration. Two configurations were compared: flat, and beds with narrow furrows, further indicated as treatments A and B respectively. The plots were planted with a *sorghum-pigeonpea* intercrop. Data from some of the plots are not reported as their outcomes were influenced by insufficient capacity of the main drainage way at high discharges, or incidentally by breaches of bunds. Still, the data show a high variability, connected to the inhomogenity of the experimental area and of the red soils in general *(table A.5.)*.

Table A.5. Runoff and soil-loss for small plots with different surface configuration (see text) for five rainstorms (1980, RW-3F)

	(a) Runoff (mm)					(b) Soil loss (t/ha)				
Date	30-7	6-8	13-8	14-8	20-8	30-7	6-8	13-8	14-8	20-8
Flat	6.2	6.6	1.8	3.8	10.0	0.35	0.39	0.06	0.23	0.73
	5.3	5.3	1.3	2.6	10.7	0.13	0.14	0.04	0.06	0.37
Beds	6.5	8.4	1.7	4.0	5.0	0.58	0.59	0.20	0.31	0.60
	6.8	7.3	2.0	5.3	7.5	0.52	0.56	0.17	0.26	0.44
	4.5	5.6	1.0	2.4	5.9	0.37	0.33	0.08	0.20	0.54
	7.4	10.0	1.7	4.2	6.5	0.29	0.28	0.06	0.17	0.20
	5.3	7.8	1.4	3.6	6.0	0.31	0.42	0.04	0.11	0.40
Ratio	0.94	0.76	0.99	0.82	1.67	0.58	0.61	0.45	0.69	1.26

(c) Rainfall characteristics

date	30-7	6-8	13-8	14-8	20-8
rainfall (mm)	23	22	13	13	56
W.M.I. (mm/h)	24	24	21	30	25

Under otherwise similar conditions, the effect of surface configuration on the occurrence of runoff and soil loss is related to the amount and intensity of a rainstorm. How the treatments compare, shows clearly through the calculation of multiple linear regressions with rainfall amount and intensity as independent variables, and as dependent variables the ratio's of runoff and soil loss of the two treatments respectively *(figure A.2.)*.

Obviously, runoff from flat plots as related to bedded plots, increases with increasing storm size and decreases with higher intensities within the range of observed storms *(section 6.2.2.)*. In respect to measured soil loss, however, the ratio between the two treatments becomes higher both with bigger storms as well as with higher intensities *(section 7.4.)*.

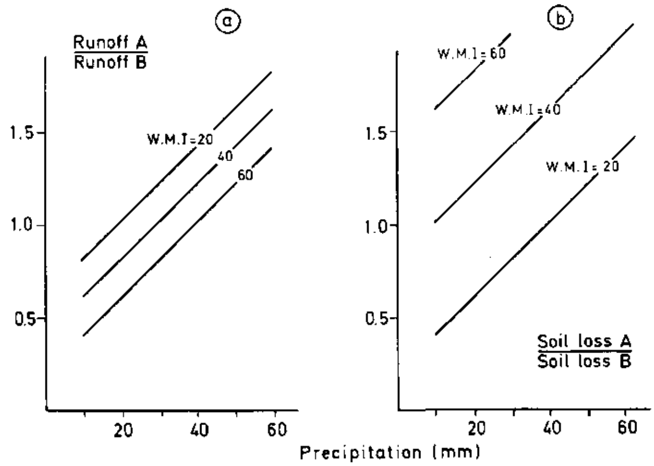


Figure A.2. Regression lines relating the ratio's of runoff (figure a) and soil loss (figure b) from a flat (A) and bedded (B) surface configuration, to rainfall characteristics (P = Precipitation (mm), W.M.I. = Weighed Mean Intensity (mm/h)).
(a) $A/B = 0.82 + 0.02\ P - 0.01\ W.M.I.$ $(R = 0.92)$.
(b) $A/B = -0.38 + 0.02\ P + 0.03\ W.M.I.$ $(R = 0.98)$.

APPENDIX 10
The Effects of Secondary Tillage on Runoff and Surface Roughness

The influences of tillage on infiltration and surface flow are complex and difficult to separate: A cultivation simultaneously breaks a crust, creates storage volume in the topsoil, induces surface micro-depression storage and increases resistance to surface flow. These effects may be partially or considerably removed as soon as the next storm occurs, depending on its size and intensity.

What can be measured is (1) the overall effect of a tillage operation on runoff and (2) the loss of surface roughness caused by rainfall and runoff.

In this specific experiment runoff from natural rainfall was measured from two adjacent plots during much of the rainy season. The area on which the plots were located had been under identical cultivation for four preceding years and had been laid out in a bed-and-furrow configuration during that period. Each of the two plots consisted of 20 beds of 1.50 m width and had a length of 60 meters. Measured slope in furrow direction was 0.8%[+)].

To observe the influences of tillage and structure destruction by rainfall at its clearest the plots were left fallow. Both plots received the same intensive primary tillage described as system 2 in section 6.1.1.1. Following each of the first two runoff producing rainfall events after field lay-out, a shallow cultivation was executed. This enabled a check to be made to see whether the two plots were comparable in their rainfall-runoff characteristics. From the third runoff producing storm onwards an increasing difference in cultivation was created by leaving an increasing number of randomly chosen beds uncultivated in one of the plots (plot B), whereas the other plot (plot A) was completely cultivated after each rain.

This implies, that of plot B area-wise only 80, 60, 40 and 20% was cultivated after storms 3 through to 6 respectively, and completely left uncultivated thereafter *(table A.6.)*.
Table A.6. gives relevant figures on observed rainfall and runoff. The last column, giving runoff values for a not-cultivated situation, are derived from the measured values of plots A and B. For this calculation it was assumed that tillage improved infiltration for the subsequent storm only and had no effect on later events.

+) The area had been originally laid out at this relatively steep slope for experimental reasons. Redirecting the fields towards the advisable slope of 0.4% would have disturbed the area to an unacceptable level.

Table A.6. Runoff as related to superficial cultivation (ICRISAT, RW-3C, 1982)

Storm Number	Date	P+)	W.M.I.+)	Fraction cultivated plot B	Runoff		
					cultivated	partly cultivated	not cultivatedx)
		(mm)	(mm/h)	-	(mm)	(mm)	(mm)
				f	A	B	B_1
1	8-7	26.7	41	1	(2.4)	(2.6)	-
2	26-7	41.4	32	1	(4.0)	(3.9)	-
3	29-7	49.8	53	0.8	16.7	17.7	21.7
4	2-9	25.0	28	0.6	2.8	5.6	9.8
5	7-9	33.5	30	0.4	4.8	7.4	9.1
6	14-9	53.7	59	0.2	23.9	30.4	32.0
7	21-9	21.8	18	0	0.4	2.6	2.6
8	22-9	12.4	8	0	0.2	2.2	2.2
9	28-9	29.1	72	0	7.4	9.6	9.6

+) P = Precipitation
W.M.I. = Weighed Mean Intensity

x) Calculated as : $\frac{B - f \times A}{1 - f}$

Multiple regression analysis, relating measured cq. calculated runoff per storm from the cultivated and not-cultivated field respectively as dependent variables, and storm size and its intensity as independent variables, gave:

$Y_A = -10.38 + 0.57 X_1$ r = 0.95 (A.10.(a))
$Y_A = -10.48 + 0.53 X_1 + 0.039 X_2$ R = 0.95 (A.10.(b))
$Y_B = -9.55 + 0.68 X_1$ r = 0.95 (A.11.(a))
$Y_B = -9.59 + 0.68 X_1 + 0.002 X_2$ R = 0.95 (A.11.(b))

With:
Y_A = Runoff from cultivated area (mm);
Y_B = Runoff from not-cultivated area (mm);
X_1 = Precipitation (mm);
X_2 = Weighed Mean Intensity (mm/hr).

Actual runoff for the two treatments increases with increasing storm size (Equations A.10.(a), A.11.(a)). Inclusion of the storm intensity as independent variable (X_2) did not improve the regression (Equations A.10.(a), A.10.(b)). From the equations and within the range of storms observed, it is clear that the rainfall intensity has an insignificant weight in determining the runoff from an individual field. However, this is different if we look at runoff differences between treatments. A stormwise comparison of the observed runoff reduction, expressed as:

$$Z = 1 - \frac{Y_A}{Y_B} \qquad \text{(A.12)}$$

with rainfall parameters X_1 and X_2 resulted in the regression line:

$$Z = 1.09 - 0.007\ X_1 - 0.009\ X_2 \qquad (R = 0.97), \qquad \text{(A.13.)}$$

that now shows a similar weight for both rainfall amount as well as intensity. It is also seen that the fraction runoff reduction through cultivation could be very high for small storms.

More insight into the runoff reduction seems to be achieved by calculating the runoff reduction from the equations A.10.(b) and A.11.(b) for different intensities. The resulting lines *(see text figure 6.2.)* both show the increase of runoff percentage with increasing storm-size as well as with increasing intensity. Figure 6.2. also indicates that at high rainfall the intensity does not play an important role.

Figure A.3.(a) gives values of the Random Roughness Index (R.R.I) in mm, for each date of observation before and just after cultivation. Total rainfall since the earlier cultivation is indicated in figure A.3.(b). The slightly higher values for R.R.I. at the early dates indicate the presence of larger clods remaining from the primary tillage operation. This part of the roughness does not contribute to the level of depression storage. Clearly, lowest values of the R.R.I. are reached following the higher rainfall events (like those on July 30, September 14 and 28). R.R.I. as measured at the end of the season did not differ much between plots with different frequency of cultivation *(table A.7.)*. Obviously, an increased number of cultivations does not significantly decrease the aggregate stability.
Figure A.3.(c) is illustrative of the decrease of roughness after cultivation by the effect of a single storm: after the first storm an equilibrium is reached which is not affected by following rainfall.

Table A.7. Surface roughness of a fallowed Alfisol by the end of the rainy season

Number of earlier cultivations	3	4	5	6
R.R.I., 28-09-1982 (mm)	2.9	2.1	2.5	2.7

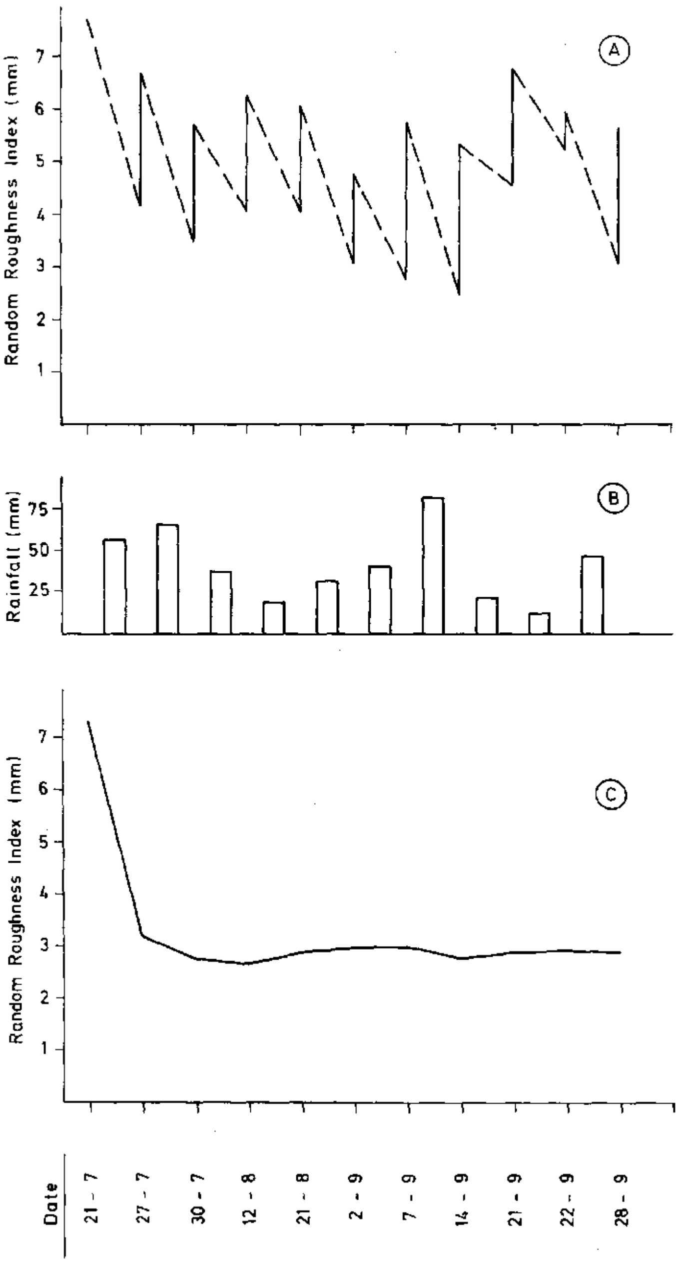


Figure A.3. Change of random roughness index in time for a fallow Alfisol with (figure a) and without (figure c) repeated cultivation.
Figure (b) indicates intermediate rainfall.

APPENDIX 11

Effects of Surface Configuration on Soil Moisture and Plant Establishment

An experiment was laid out to compare two surface configurations, flat and broadbeds. Individual plots had a size of 4.5 by 26 meters with four replications. A pearl millet crop was planted on August 2nd. During the subsequent two months gravimetric moisture sampling was done up to a depth of 30 cm and at 5 cm vertical intervals on a total of 13 dates *(table A.8.)*.

Measurements on layerwise root density at 10 cm intervals, on leaf area and its dry matter weight were done on three occasions *(see text, section 6.1.3., table 6.2. and figure 6.7.)*.

The soil had a rather dense packing, with bulk density values of about 1.5 - 1.7 in the top 5 cm and 1.8, incidentally 1.9, below. Correspondingly, the pore fraction of the different layers can be calculated as being of the order of 40% for the top 5 cm and about 30% below that. Field capacity must be less than this value and from the figures in table A.8. it is clear that on most dates the profiles are at field capacity and even approximate the point of saturation. Reduction of plant growth due to insufficient aeration is to be expected in such situations. It apparently occurred most heavily on the flat cultivated plots *(see text section 6.1.3.)*.

Table A.8. Volumetric water content (%) for different layers at different dates for two land management treatments+) (RA-10, 1978)

depth	August					September							
(cm)	2	5	9	12	31	6	9	12	16	19	23	27	30
Flat													
0-5	21	24	24	21	26	29	21	23	26	31	33	32	22
5-10	28	30	30	27	30	30	25	22	28	31	30	35	28
10-15	27	25	27	25	26	31	21	22	26	28	27	31	24
15-20	26	25	26	25	29	29	23	22	22	26	26	26	25
20-25	28	23	27	27	30	27	25	24	23	28	27	27	27
25-30	28	24	24	27	29	29	26	24	25	26	25	25	26
Beds													
0-5	22	24	22	18	31	25	27	23	26	31	32	34	22
5-10	29	28	31	28	32	30	30	22	29	32	32	36	25
10-15	26	25	29	27	27	28	25	21	30	32	27	32	25
15-20	27	27	25	25	27	27	23	22	29	29	27	29	25
20-25	29	27	26	25	28	30	25	24	28	26	30	29	28
25-30	28	27	24	23	26	30	25	26	25	26	31	23	25

+) Given values are mean values of four replications with three sub-samples each

The frequent rainfall during the month of September kept the soil almost saturated. Under these circumstances no differences between the treatments could be established. Therefore also, the difference in water use from the flat and bedded treatments, as would be expected from the difference in crop development, could also not be traced.

APPENDIX 12

Observations on the Effects of Depression Storage on Runoff. Sprinkled Plots

For this experiment small runoff plots were used of 2 x 1.5 meter. They were bordered by metal sheets, driven into the soil to a depth of about 10 cm and with an outlet at the lower side. The plots were located in a 2% sloping area while their longitudinal direction coïncided with a 0.4% slope. Artificial rain could be applied by a set of 13 sprinklers, tested to apply a constant rainfall intensity of 18 mm/h with a co-efficient of uniformity (Christiansen) of more than 90%. Runoff from individual plots was measured through collection of the water in buried buckets, that were emptied when full or weighed when partly full. The lay-out of the 16 plots, with 4 treatments, was made with a randomised block design.

The experiment could only be run on three dates, with different initial moisture condition of the soil. Apart from this difference in antecedent moisture the variability in soil characteristics of the area and possibly errors connected to lay-out of the experiment also influenced the measurements. The data, therefore, also show a high variation within the treatments and observed differences were not significant. However, the trend that differences in depression storage influence runoff at lower rainfall only, is clearly evident, as it was hoped to show *(see text, section 5.2.1.)*.

In general, the high variability of soil characteristics within a field might be accounted for as an important constraint in experiments to measure individual components of the water movement. Small plots cannot be considered as representative for a larger area. With larger sized plots both the application of artificial rainfall and the accuracy of measurements present difficulties. (Sibie, 1971; Sharp and Holtan, 1940).

APPENDIX 13

Hydraulic Measurements on Differently Shaped Furrows

A known and constant discharge of water was released at the top of two narrow and two wide furrows of 50 meters in length. Outflow at the lower end was monitored. In each furrow two or three different discharges were applied. The inflow was regulated using calibrated siphons taking the water from a barrel in which the water level was kept at a near constant level. Inflow was continued until a constant outflow was measured. The cross-sections of the furrows at 10, 20, 30 and 40 meters from the top were measured with a relief meter with pins at 2.5 cm interval; the height of flowing water was monitored with a point-gauge. Table A.9. lists the inflow rates that were being used and the observed outflow.

On the basis of detailed surveys of the longitudinal section of the furrows, the relative heights of the points of measurement were also known. Together with the measurements on depth of the flowing water, the hydraulic slope at two points in each furrow was estimated. An estimate of the local discharge was based on the difference between in- and outflow and on the assumption that infiltration was related to the differences in wet perimeter. Values were used in the Manning flow equation, which yielded the values K for different discharges and different cross-sections *(table A.10.)*.

From the same and similar furrows runoff was measured during natural rainfall. Outflow from single furrows was measured with the help of a calibrated slotted device and buried 200 liter drum. The capacity of this measurement structure did not exceed 10 mm per storm. Details on rainfall and runoff are given in table A.11.

Table A.9. Equilibrium inflow and outflow rates of differently shaped furrows (RW-1C, 1979)

Plot number	Furrow shape	Inflow (l/s)			Outflow (l/s)			Outflow (%)		
		(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
11 B	narrow	0.33	0.63	0.88	0.18	0.40	0.75	55	63	85
17 B	narrow	0.30	0.58	-	0.14	0.29	-	45	50	-
10 C	wide	0.33	0.58	0.88	0.09	0.23	0.58	28	40	65
13 C	wide	0.33	0.58	0.88	0.09	0.27	0.52	28	46	58

Table A.10. Calculated values for hydraulic roughness of two types of furrows in an Alfisol ("K-Manning"), for different inflow rates

		Inflow rate at top (l/s)		
		0.33	0.58	0.88
Plot number	Distance from top	Hydraulic roughness (K-Manning)		
	(m)	($m^{1/3}$ s^{-1})		
Narrow furrows				
17	20	11.1	18.6	-
	30	9.8	13.1	-
11	20	14.9	14.3	15.5
	30	10.8	14.3	16.9
Wide furrows				
13	20	5.4	7.4	7.2
	30	5.3	8.6	9.6
10	20	3.3	5.1	7.5
	30	-	-	-

Comparing the mean runoff from narrow and wide furrows per storm, it is seen that their ratio stays below unity for low intensive storms (those with a weighed mean intensity not exceeding 20 mm/h). For more intensive storms the ratio B/C exceeds unity. This relation has been worked out further, using multiple linear regression, as:

$$B/C = 0.72 + 0.004\ P + 0.010\ WMI \qquad (R = 0.92) \qquad (A.14.)$$

(see also text, *figure 6.13.*, *section 6.2.3.*).

Table A.11. Runoff from two types of furrows; B: narrow, C: wide. (RW-1C, 1979)

furrow type		date							
B	C	28/7	28/8	11/9	14/9	25/9	26/9	1/10	5/11
plot number		runoff (mm)							
	5	-	6.0	-	10	2.2	3.2	2.6	5.8
6		10	1.5	4.6	7.9	2.3	3.1	2.5	4.8
	7	-	1.8	4.4	6.8	1.0	1.0	0.9	2.0
8		-	-	-	-	1.6	2.5	2.4	4.0
	9	-	3.9	7.1	10	2.8	3.8	3.1	5.3
	10	7.8	4.2	6.7	8.4	1.9	2.3	2.5	9.3
11		-	4.5	7.0	8.3	1.9	1.8	1.8	10
	12	9.8	-	5.5	5.7	2.2	4.3	2.5	8.1
	13	6.1	3.9	9.1	8.6	1.2	0.6	0.8	3.3
14		8.4	4.8	8.9	10	2.3	2.9	2.5	8.5
	15	-	3.5	6.7	8.7	1.9	2.0	2.2	6.5
	16	7.2	4.2	8.1	10	2.4	3.2	1.8	8.7
17		10	5.8	7.6	9.1	1.1	0.9	0.9	10
B (average)	:	9.5	4.2	7.0	8.8	1.8	2.2	2.0	7.5
C (average)	:	7.7	3.9	6.8	8.5	2.0	2.6	2.0	6.1
ratio B/C	:	1.23	1.08	1.03	1.04	0.90	0.85	1.00	1.23
Rainfall (mm):		36	34	22	32	10	17	17	30
W.M.I. (mm/h):		32	36	24	25	18	8	20	41

APPENDIX 14

The Water-Balance near a Contour-Bund

In the 1980 monsoon season, stagnating water could be observed during a total of 10-15 days for different bunds in sub-watershed RW-3B. An automatic water level recorder, located near the spillway of one of the bunds registered the fluctuations of the level of the ponded water. Evaporation from the standing water was measured with the help of an evaporation pan, located in the area of submergence near the same bund. Through an accurate land survey the relation between water level and stored volume behind the bund was deduced.

For the bund under observation the maximum quantity of water that could be held, amounted to 17 mm on total field basis. Any excess runoff would overflow a spillway and leave the area. On the basis of the observations, table A.12. could be constructed, indicating the quantity of stored water, expressed as mm over the entire field. Of the total of 84 mm runoff water, 47 mm or 56% was temporary stored within the bunded field. Most of this water (85-90%) infiltrated, 10-15% evaporated.

The longest period of water stagnation occurred from August 18 till 26. Details of the water balance during this period are given in figure A.4. On August 18 field runoff amounted to 27 mm, of which 17 mm was stored behind

Table A.12. Runoff water kept behind bund 2 (RW-3B) or discharging (1980)

Date	Rain	Water stagnating		Flow through spillway	
	(mm)	(mm)		(mm)	
14-6	16.0	2.0			
15-6	8.0	1.9			
21-7	9.5	0.7			
22-7	31.2	2.6			
29-7	20.0	1.5			
5-8	17.0	2.4			
13-8	12.0	1.0			
14-8	12.8	2.8			
18-8 (a)	16.0	1.7			
(b)	86.0	16.4		10.4	
19-8 (a)	11.2	3.8			
(b)	44.0	1.1		26.0	
1-9	30.5	0.9			
2-9	14.5	1.9			
5-9	28.0	4.5			
18-9	16.5	0.5			
24-9	15.5	1.5			
Total		47.2	+	36.4	= 83.6
% of season's rainfall		6.3	+	4.9	= 11.2

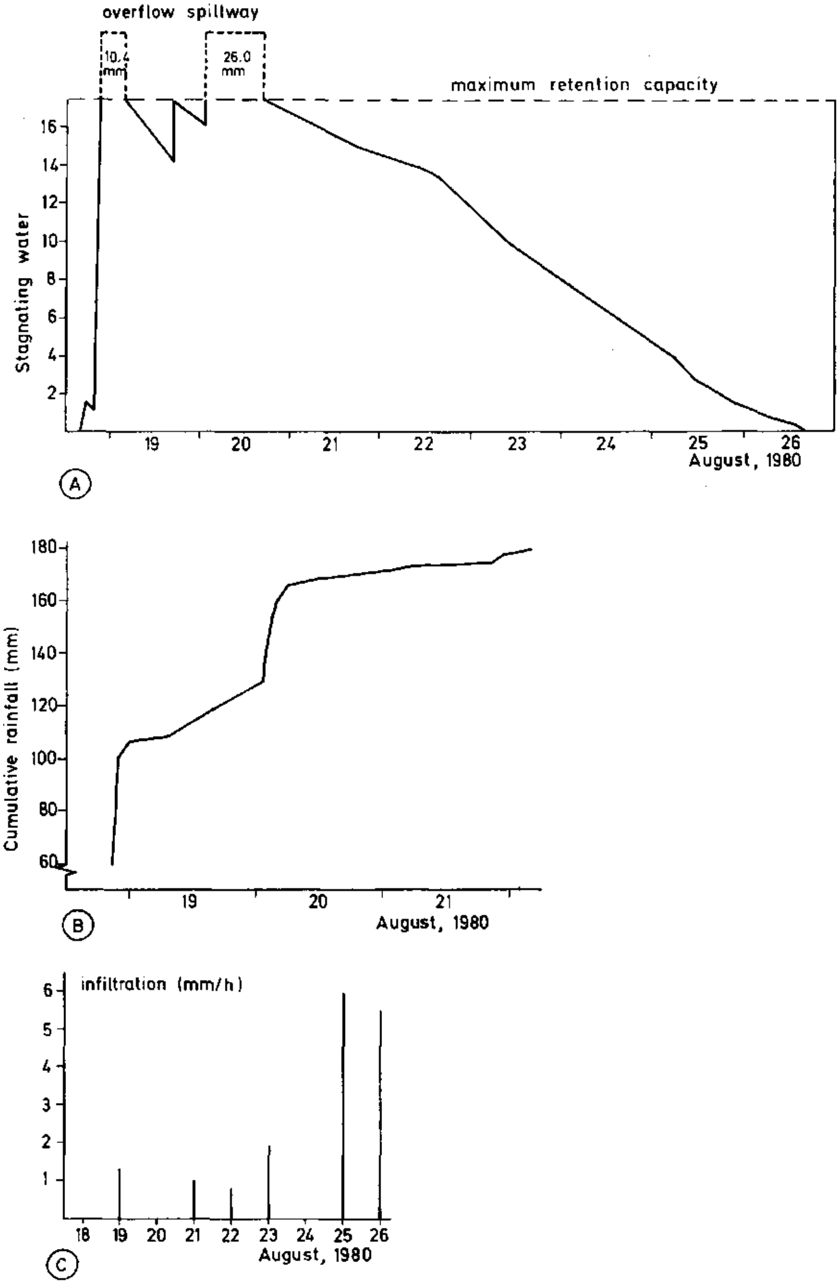


Figure A.4. Water balance near a contour-bund during the period of August 18-26, 1980. (RW-3B, field 2). (a) Stagnating water (mm on total area base), (b) cumulative rainfall (mm), (c) infiltration in ponded area (mm/h) the bund and 10 mm was removed through the spillway. The runoff caused by the subsequent rain one day later, however, came almost completely to field outflow, as only 1 mm of storage capacity had become available at that time. This indicates the importance of sufficient outlet- and waterway capacity, even in contour-bunded areas.

The rate of recession of the standing water, mainly through infiltration, varies strongly during the season. During the period under consideration, infiltration rate came down to 1 mm/h, while it had been observed to be about 6 mm/h earlier in the season. In periods of extended flooding, observed infiltration rates are distinctly lower than in periods with minor ponding. This can also be seen in figure A.4.(c) where infiltration rates become higher again by the end of the period of ponding. The lower infiltration may be explained by a restriction of the lateral flow component underneath the bund. With a lower area ponded, its relative importance decreases.

APPENDIX 15

The Influence of Contour-Bunds on Crop-Yield

Figures A.5. and A.6. depict observed yield levels across contour-bunded fields at ICRISAT station for two years. Each point indicates the local yield at a certain distance from the bund and is based on three or four yield samples of 12 m^2 each per field.
The bunds were constructed in 1978 in a 2.5 ha sub-watershed (RW-3B), dividing this area into four fields. The vertical interval between the bunds was 90 cm, height of the bunds 60 cm with a spillway at 30 cm height.

During the first season after construction, characterised by prolonged wet spells, an overall yield reduction was observed for both sorghum and pigeonpea *(section 6.3.1.)*. This was partly ascribed to water stagnation, partly to the loss of productive land under the bunds and borrow-pits. To try to exclude the latter effect, borrow-pits near three of the bunds were filled with top soil before the next growing season, leaving the other bunded field as a control.

Figure A.5. shows the yields in the subsequent season (1979). Although pearl millet yield was lowest in the remaining borrow-pit area of field 4 *(figure A.5.(a))*, a higher than average yield could be observed near the bunds in field 2 *(figure A.5.(b))*. This favourable situation, however, should also be seen in the context of the rainfall pattern of that specific year. Hardly any runoff occurred before the harvest of the pearl millet crop. Only after that date and with a maturing sorghum crop (fields 1 and 3), a wet period occurred with a few days water stagnation. Such short period of water stagnation, however, does not affect sorghum adversely (Doggett, 1970). Even so, the higher yield near the bunds could only balance the yield reduction, caused by the loss of land *(Figure A.5.(c))*.

In contrast to sorghum, pearl millet is more sensible to waterlogging (Purseglove, 1972). This came out clearly in the 1980 season in which year a period of water stagnation occurred in August *(Appendix 14)*. Yield of pearl millet was very much reduced, particularly near the lower bund *(Figure A.6.)*.

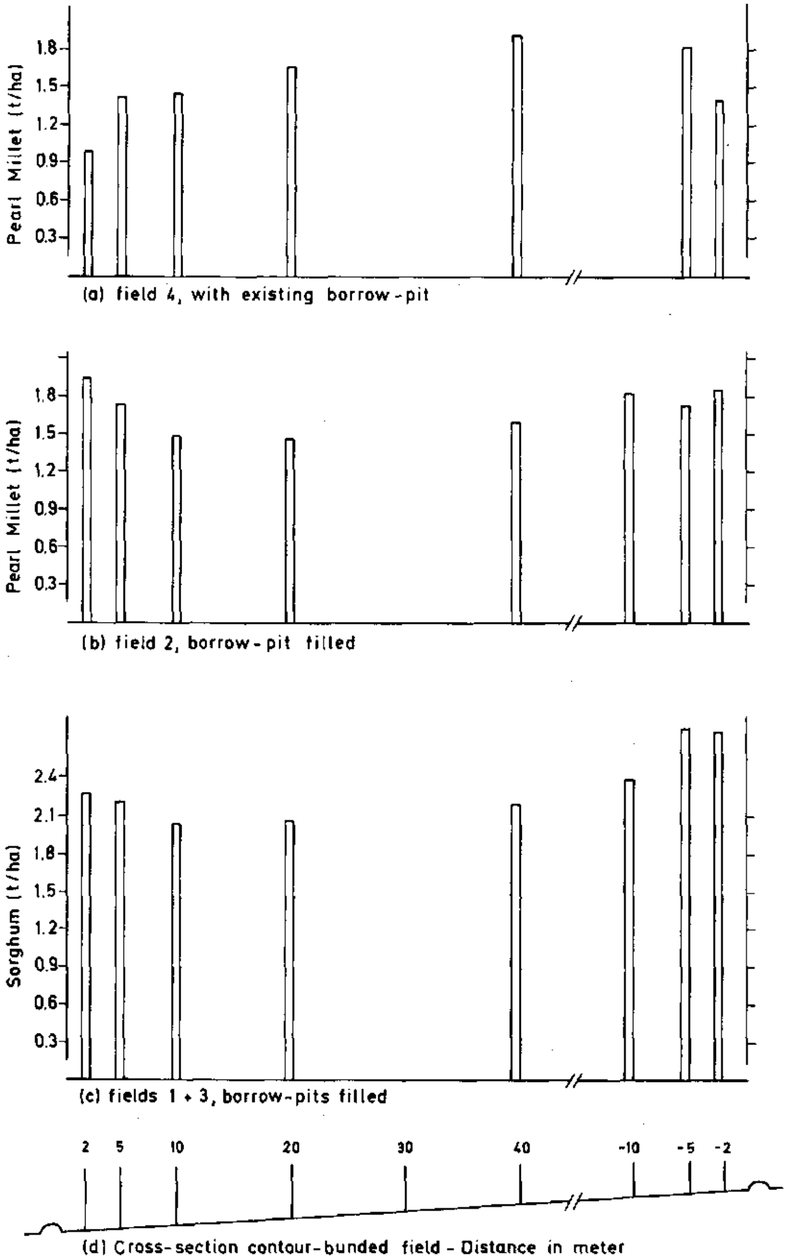


Figure A.5. : Yield of pearl millet and sorghum (t/ha) across four contour-bunded fields, second year after construction, with borrow-pits filled in field 1, 2 and 3. (RW-3B, 1979).

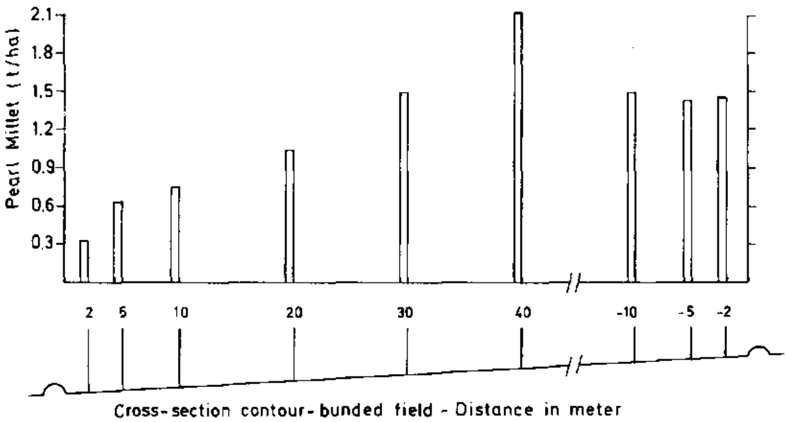


Figure A.6. : Yield of pearl millet (t/ha) across contour-bunded fields 2 and 4 (RW-3B, 1980).

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GLOSSARY

Agricultural watershed: Here used as the indication of an area, generally not exceeding 20 ha, from which the surface runoff water collects at one determined point, and which area is mainly or exclusively in agricultural use.

AICRPDA: All India Co-ordinated Research Project on Dryland Agriculture.

Bund: Earthen wall, thrown up with local material, with a cross-sectional size that depends on its function.

Contour-bund: Earthen wall, constructed across a field or at its boundary, that follows the contour. As a rule, contour-bunds are provided with a spillway to avoid over -topping and hooked up with side-bunds at the two extremes.

Dam: A wall or bank built to keep back water, also commonly used to mean the barriers that obstruct flow in furrows (see: Tied ridging).

Diversion dam: Earthen wall that is constructed to hold surface runoff and to lead this water to a predetermined spot or channel.

Dry farming: Techniques of non-irrigated farming in arid areas, through which more water is made available to the crop than is received by it from rainfall on the occupied area during its growing cycle.

Farming system: The entity of available technology, the decisions the farmers make and the circumstances that directly influence these.

Field bund: Small earthen wall to indicate a field boundary.

Graded bund: Earthen wall constructed in a direction slightly deviating from the local contour-line and provided with an outflow.

ICRISAT: International Crops Research Institute for the Semi-Arid Tropics.

Rainfed farming: The growing of crops that fully depend on the local precipitation, occurring during the growing cycle.

Reservoir: Place where water is stored, here generally relating to an excavated pond of moderate size.

Runoff collection: The diversion of, naturally occurring, runoff water into a created reservoir.

Runoff farming: The growing of crops in fields that partly or fully depend for their water supply on the inflow of water from treated or untreated catchments.

SAT: Semi-Arid Tropics.

Sub-watershed: A part of a larger watershed area.

Tank: The usual name in India for a reservoir that is created by damming a valley in the lower reach of a watershed.

Tied ridging: A land management system in which furrows are closed at regular intervals by small earthen dams to prevent water from running off.

Water harvesting: All techniques that stimulate runoff from unproductive areas and the subsequent diversion of the runoff water to a storage reservoir (possibly the soil profile).

W.M.I.: Weighed Mean Intensity (of a rainstorm) See section 5.2.2.

Watershed: The undivided area which runoff water collects at one point.

Curriculum Vitae

The author was born in Rotterdam, the Netherlands, on January 7th, 1949. He attended secondary school at the Franciscus College in Rotterdam, which he finished in 1968. In that year, he began his studies on land- and water-management ("tropische cultuurtechniek") at the State Agricultural University Wageningen, the Netherlands.

During his studies he stayed for a 6-month period in Santa Cruz, Bolivia, where he worked as assistant in soil survey and irrigation development. After graduation in 1976, he worked as a tutor for the International Course on Land Drainage, organised by the International Institute for Land Reclamation and Improvement (ILRI) at Wageningen.

From March 1977 until 1981 (through a contract with the Directorate General for International Co-operation (DGIS) of the Government of the Netherlands), he was connected as junior scientist to the Farming Systems Research Program of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) at Hyderabad, India, which institute he visited again during July 1982. There he carried out field-experiments on aspects of land- and watermanagement. From March 1981 he has been working at the Department of Irrigation and Civil Engineering of the State Agricultural University, during which period he introduced a course-element on land- and watermanagement of rainfed farming in tropical areas.

ABSTRACT

Huibers, F.P. (1985). Rainfed agriculture in a semi-arid tropical climate. Aspects of land- and watermanagement for red soils in India.
Doctoral thesis, Agricultural University Wageningen, the Netherlands, XI, 193 p., Ill., Summary in Dutch.

Red soils in a semi-arid tropical climate pose specific problems for the production of rainfed crops. The instability of their top soil and their generally low profile water retention capacity induce rainfall-runoff and a too low level of available water to bridge droughty periods within the growing season, even in areas where mean annual rainfall seems to be sufficient to grow (adapted) crops. Common agricultural practices in red soil areas of India are characterised by a low level of inputs and low yields, typical for subsistence farming.
Techniques of land- and watermanagement that would improve the ability to control runoff and erosion are discussed. Collection of runoff water for subsequent use as supplementary irrigation is thought to be a prerequisite for distinct increases in crop production and reduction of risk for the farmers, for all but the deepest soil profiles. Approaches to improve the productivity should include those of resource protection and should fit the farmer's level of technology. Individual land units of small size seem most appropriate and efficient for reaching these goals.